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Very Large Telescope

Paranal Science Operations

FORS2 User Manual

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Chapter 1

Introduction

1.1 Scope

The FORS2 User Manual is intended to cover all aspects of the VLT instrument FORS2 following the merging of FORS1 and FORS2 in 2008. It is intended to give comprehensive information on the following topics:

- Overall description of the FORS2 instrument
- Observing with FORS2
- Calibrating and reducing FORS2 data
- Supplementary Data and Informations about CCDs, filters and grisms

The informations about observation block preparation for FORS2 with p2pp and mask preparation with FIMS are given in the following supplementary manuals:

- FORS FIMS Manual (ESO document VLT-MAN-ESO-13100-2308)
- FORS Template Manual (ESO document VLT-MAN-ESO-13100-2309)

The knowledge of these manuals is essential for the preparation of proposals and observations with FORS2.

1.2 More Information on FORS2

The FORS2 User, FIMS and Templates Manuals are published on the FORS instrument WEB page. Additionally, a version of the user manual from P82 can be found which has information on FORS1 and FORS2 prior to the merger:

http://www.eso.org/sci/facilities/paranal/instruments/fors/

Information and software tools for the preparation of service and visitor mode observations with FORS2 are given under:

http://www.eso.org/sci/observing/phase2.html

Visiting astronomers will find instructions and hints on the Paranal Science Operations WEB page and the Paranal Observatory home page:

http://www.eso.org/sci/facilities/paranal/
http://www.eso.org/sci/facilities/paranal/sciops/

1.3 Contact Information

In case of specific questions related to Service Mode observations and proposal preparation please contact the ESO User Support Department:

usd-help@eso.org

For visitor mode observations please contact the Paranal Science Operations Team:

pso@eso.org

1.4 Acknowledgements

The first edition of this User Manual was delivered by the FORS Consortium which was formed by the Landessternwarte Heidelberg, the University Observatories of Göttingen and Munich in the scope of the FORS contract and finally compiled and edited by G. Rupprecht. Later editions were made by H. Böhnhardt, T. Szeifert, E. Jehin and I. Saviane.

We are very grateful for the input from the members of the FORS instrument operation team and from the team of the Paranal Observatory, and last but not least for the feedback from the users. The P93 version has benefited by a careful scrutiny by M. Krumpe.

Chapter 2

Instrument Characteristics

2.1 Overview

Instrument Concept: FORS2 is the visual and near ultraviolet **FO**cal **R**educer and low dispersion **S**pectrograph for the **V**ery **L**arge **T**elescope (VLT) of the **E**uropean **S**outhern **O**bservatory (ESO). Two versions of FORS were built and installed at the Cassegrain foci. They have been moved to different telescopes over the years. As of P83, FORS1 was decommissioned to make way for the second generation of VLT instrumentation.

FORS was designed as an all-dioptric instrument for the wavelength range from 330 nm to 1100 nm and provides an image scale of 0.″25/pixel (and 0.″125/pixel) with the standard resolution collimator (and the high resolution collimator, respectively) in the default binned (2x2) read-out mode of both FORS detectors. Since April 2009, FORS2 has been available with a choice of components from both of the original FORS1 and FORS2 instruments. FORS2 is equipped with a mosaic of two 2k×4k MIT CCDs (pixel size of 15×15 μm) and particularly sensitive in the red part of the spectrum (up to 1100 nm). The detector previously mounted on FORS1 is also available (in Visitor Mode only). It consists of a mosaic of two 2k×4k E2V CCDs (pixel size of 15×15 μm) particularly sensitive in the blue range of the spectrum.

The main instrument components shown in Figure 2.1 are: The *Top Section* with the focal plane equipment including the multi object spectroscopy (MOS) unit with 19 movable slits, the longslits, the polarimetry mask, the MXU mask exchange unit and the two calibration units. The *Collimator Section* with the two collimators and the electronic cabinets. The *Filter/Camera Section* with the retarder plate mosaics, the wheel for the Wollaston prism and optional optical analyzers (filters and/or grisms), the grism wheel and the broadband filter wheel in the parallel beam. Furthermore the camera, the interference filter wheels in the converging beam and the exposure shutter in front of the CCD.

Observing Modes: FORS2 offers the observing modes tabulated below. While the observing modes IMG, LSS, and IPOL are supported for both collimators, some restrictions apply in the modes MXU, MOS, HIT, and PMOS:

direct imaging	IMG	
imaging with occulting bars	OCC	
imaging polarimetry	IPOL	
multi-object spectro-polarimetry	PMOS	SR-collimator only
multi-object spectroscopy with masks	MXU	SR-collimator only
multi-object spectroscopy with movable slitlets	MOS	SR-collimator only
longslit spectroscopy	LSS	
high time resolution imaging and spectroscopy	HIT	SR-collimator only

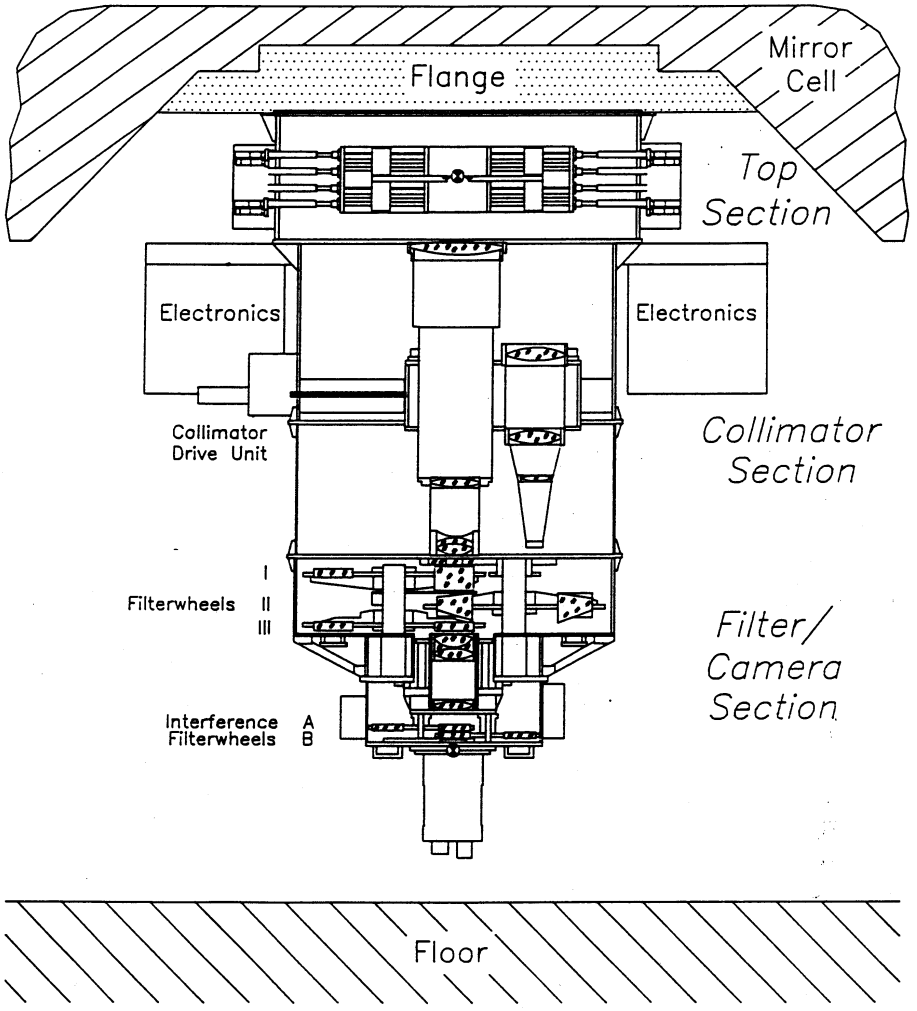


Figure 2.1: Schematic view of the FORS instruments

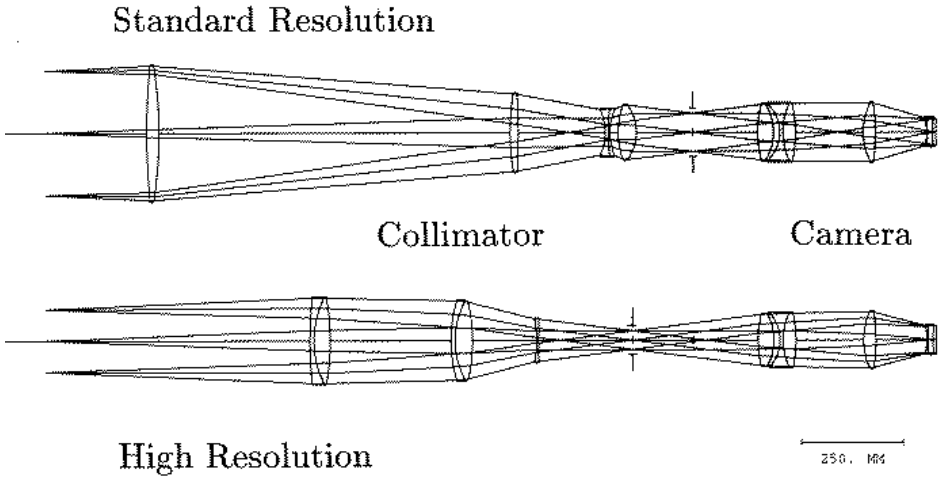


Figure 2.2: Light paths for the standard and high resolution collimators.

2.2 Standard Instrument Configuration

FORS2 is operated with a standard configuration with certain opto-mechanical components permanently mounted in fixed positions. This instrument configuration is kept frozen for a given observation period to ensure that all observations in service or visitor mode can be taken at any time without delays due to configuration changes. The current standard configuration is listed below in Table 2.1. The interference filters given in Table 2.3 and up to 10 MXU masks will be mounted on user request.

Please note that the instrument standard configuration will be only modified in exceptional cases upon request and with the approval of ESO. Such requests should be submitted to usd-help@eso.org before the beginning of the observing period with a justification for the changes.

Instrument Location	P2PP Entry Name	Component Name
Focal area	MOS	19 slitlet multi-object spectroscopy unit
	LSS	9 slit longslit mask unit
	MXU	mask exchange unit for multi-object spectroscopy with up to 10 masks
	polarimmask	Mask unit for imaging polarimetry with HR collimator
Collimator unit	COLL_SR+6	Standard resolution collimator
	COLL_HR+7	High resolution collimator
Retarder swing arm	RETA4+4	Quarter wave plate mosaic
	RETA2+5	Half wave plate mosaic
Wheel 1 (Wollaston wheel)	WOLL_34+13	Wollaston prism
	g_HIGH+115	Standard g-band filter
	GRIS_150I+27	Grism 150I
	GRIS_600RI+19	Grism 600RI
	GRIS_600z+23	Grism 600z
	z_GUNN+78	Standard z-band filter
Wheel 2 (grism wheel)	GRIS_1028z+29	Grism 1028z
	GRIS_1400V+18	Grism 1400V
	GRIS_600B+22	Grism 600B
	GRIS_1200B+97	Grism 1200B
	GRIS_1200R+93	Grism 1200R
	GRIS_300I+11	Grism 300I
	GRIS_300V+10	Grism 300V
Wheel 3 (broadband filter)	u_HIGH+112	Standard u-band filter
	GG435+81	Order sorting filter GG435
	OG590+32	Order sorting filter OG590
	b_HIGH+113	Standard b-band filter
	v_HIGH+114	Standard v-band filter
	R_SPECIAL+76	Standard R-band filter
	I_BESS+77	Standard I-band filter

Table 2.1: FORS2 standard configuration of opto-mechanical components.

Exchangeable Components: up to 8 interference filters can be installed in FORS2, in addition to the standard configuration set-up. For visitor mode observers, the appropriate filter set-up request referring to the available filters of Table 2.3 has to be submitted to the Paranal Science Operations Group at least one day before the start of the observing program. For service mode, a maximum of two interference filters per OB can be asked. Paranal Science Operations will take care of the proper instrument set-up for the observations. Special rules and recommendations apply for the use of user provided filters: see Section 2.3.3.

Filter and Grism Combinations: In general only one filter can be used per instrument setup for imaging and one grism (plus the recommended order separation filters in Table 2.4 if needed) for spectroscopic modes. The combination of one grism with one filter, other than the order separation filters is only supported if the two components are mounted in different wheels. However, these non-standard configurations are not supported by the calibration plan, as described in Section 4.1. The combination of two filters at the same time are generally not supported in normal operation since these setups would require testing and software reconfiguration.

Components and modes that are no longer offered: please see Appendix H

2.3 Direct Imaging — IMG and OCC modes

2.3.1 Basic Characteristics of the Imaging Optics

Field of View, Pixel Resolution, Transmission, Image Quality: FORS2 reduces the VLT Cassegrain image scale of 528 μm/arcsec to 0.″25/pixel with the standard resolution collimator and 0.″125/pixel with the high resolution collimator and the binned (2x2) 15 μm pixels of the MIT CCD mosaic as well as for the binned (2x2) 15 μm pixels of the E2V CCD mosaic. Please take the accurate scales and information about the image field distortion from Section 4.2. Sky concentration effects will be small and negligible for flat-field and photometric calibrations.

	Standard Resolution	High Resolution
Image Quality	80 % in 0.″2	80 % in 0.″1
	within 4.′0	within 2.′0
collimator focal length	1233 mm	616 mm
camera focal length	280 mm	280 mm
final f-ratio	3.13	6.25
MIT mosaic		
Pixel Scale (2x2)	∼0.″25/pixel	∼0.″125/pixel
Pixel Scale (1x1)	∼0.″125/pixel	∼0.″0632/pixel
Field of View	6.′8×6.′8	4.′2×4.′2
E2V mosaic		
Pixel Scale (2x2)	∼0.″25/pixel	∼0.″125/pixel
Pixel Scale (1x1)	∼0.″125/pixel	∼0.″0632/pixel
Field of View	6.′8×6.′8	4.′2×4.′2

Table 2.2: Optical properties of FORS2

Field vignetting and detector geometry with the FORS2 CCD mosaics: The field of view of FORS2 with the MIT/E2V CCDs is restricted by the MOS unit in the focal plane of the unit telescope to about 6.8×6.8 arcminutes for the standard resolution collimator. In case of the high resolution collimator the corners of the field of view are vignetted by the camera lenses. The two CCDs of each mosaic are mounted slightly offset from the optical axis by 33″ for operational reasons. The center of the field of view will fall on y-pixel ∼260 of the upper "chip1" CCD for unbinned standard resolution mode. Images showing the respective vignetting pattern for the standard (MOS) and high resolution collimator mode can be found in Appendix G of this manual.

High resolution imaging with the FORS2 CCD mosaics: With the high sampling of the MIT/E2V CCDs of 0.″125/pixel for the unbinned 15 μm pixels it is possible to operate with the standard resolution collimator down to seeing values of about 0.″35 without performance losses in respect to observation with the high resolution collimator. Below seeing values of 0.″3 the high resolution collimator is expected to improve the image quality in a significant way.

2.3.2 The FORS2 Filter Set

Standard Broadband Filters: FORS2 provides positions for 7 broadband filters in any of the three wheels of the parallel beam section and for 8 interference filters in two wheels of convergent beam section. The standard filter sets for FORS2 are the four new high throughput broad band filters previously mounted in FORS1 u_HIGH, b_HIGH, v_HIGH, g_HIGH, together with the R_SPECIAL, I_BESS, z_GUNN (see Figure 2.3) and some order separation filters (see Table 2.1). The special R band filter and the Bessel I filter of FORS2 show internal fringes at a faint level. In case of the Bessel I, the internal fringes can only be seen with the IR optimized MIT detectors. In both cases the typical shape of the pattern is circular and off-axis. The complete list of filters together with the transmission curves are presented in Appendix B of this manual.

Order Separation Filters: the order separation filters are foreseen for spectroscopic applications in the first place, but they are also available for imaging exposures. They have an edge-shape transmission curve with

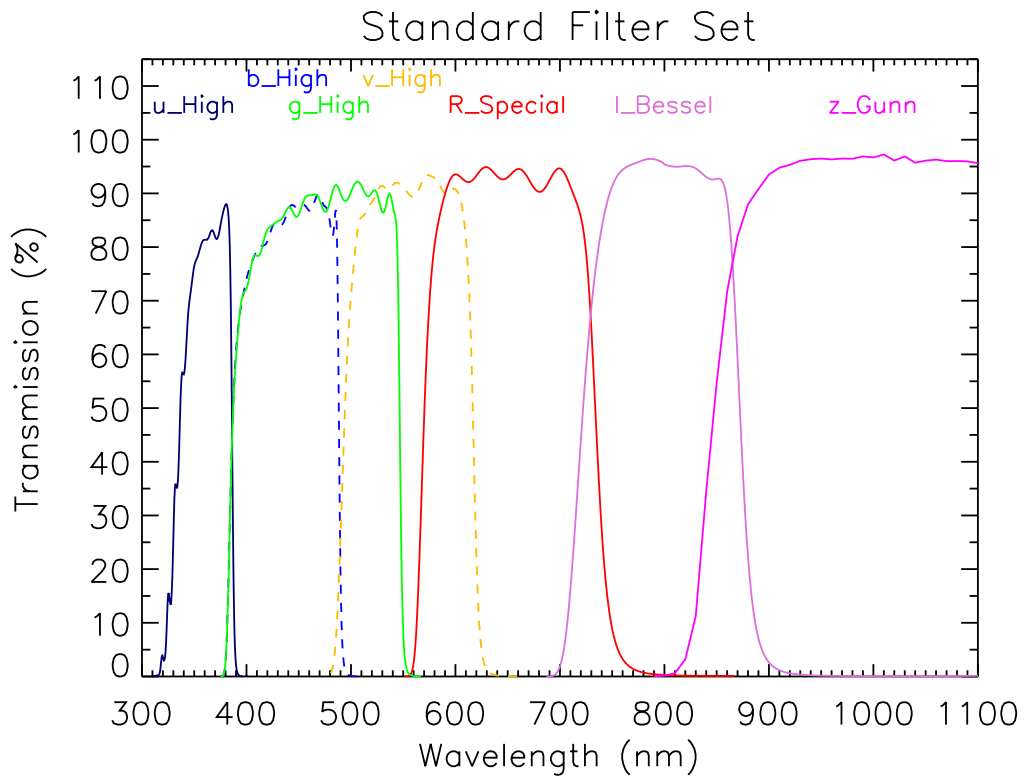


Figure 2.3: The FORS2 filters which can either be used in the ubvRIz sequence or the ugRIz sequence to cover the full wavelength range with broad band filters.

cut-off wavelength designed to match the respective grisms for spectroscopy. The order separation filters are installed in the parallel beam of the instruments.

Interference Filters: the standard interference filters available for FORS2 are centered on important emission lines and on wavelengths 5 and 10% longer. The interference filters are located in the convergent beam in the camera and have a diameter of 115 mm. Their wavefront error is less than $\lambda/4$ within 25 mm.

The intrinsic transmission curves of the narrow band filters have approximately Gaussian shape. The central wavelengths of the interference filters depend on the tilt angle of the incident beam. Therefore, all interference filters of FORS2 are used in the convergent beam to minimize the field dependence of the filter curves. For the given focal ratio of FORS2 the maximum recommended filter resolution $\lambda/\Delta\lambda$ will be 100 (SR) and 400 (HR collimator). Filter curves that are narrower than this will be convolved and will only lead to a decrease in transmission. The measured transmission parameters of the narrow band filters for the convergent beam are summarized in Table B.2.

Medium band Interference Filters: a few intermediate band filters are available. Table B.2 lists the filter names and the transmission characteristics, while Figure B.2 shows the transmission curves of the filters.

Image Offsets: The sources of image offsets are the small flexures of FORS2 and the atmospheric dispersion, both of which are relatively small effects. The later is corrected by the atmospheric dispersion corrector, such that there should be no significant image offsets between the telescope guiding system and the respective images taken with FORS2 for zenith distances of up to 45 degrees (it gives a partial correction even at larger zenith distances).

P2PP entry	Filter type
OII+44	O II filter
OII/4000+45	O II filter redshifted by 4000 km/s
OII/8000+46	O II filter redshifted by 8000 km/s
HeII+47	He II filter
HeII/3000+48	He II filter redshifted by 3000 km/s
HeII/6500+49	He II filter redshifted by 6500 km/s
OIII+50	O III filter
OIII/3000+51	O III filter redshifted by 3000 km/s
OIII/6000+52	O III filter redshifted by 6000 km/s
HeI+53	He I filter
HeI/2500+54	He I filter redshifted by 2500 km/s
HeI/5000+55	He I filter redshifted by 5000 km/s
OI+56	O I filter
OI/2500+57	O I filter redshifted by 2500 km/s
OI/4500+58	O I filter redshifted by 4500 km/s
H_Alpha+83	H Alpha filter (replacement for H_Alpha+59)
H_Alpha/2500+60	H Alpha filter redshifted by 2500 km/s
H_Alpha/4500+61	H Alpha filter redshifted by 4500 km/s
SII+62	S II filter
SII/2000+63	S II filter redshifted by 2000 km/s
SII/4500+64	S II filter redshifted by 4500 km/s
SIII+65	S III filter
SIII/1500+66	S III filter redshifted by 1500 km/s
SIII/3000+67	S III filter redshifted by 3000 km/s
FILT_485_37+68	special intermediate-band filter
FILT_691_55+69	special intermediate-band filter
FILT_815_13+70	night sky suppression filter
FILT_834_48+71	night sky suppression filter
z_SPECIAL+43	Special z-band filter (width 20nm)
FILT_917_6+88	Special z-band filter (width 6nm)
FILT_530_25+84	Munich intermediate-band filter
FILT_500_5+85	Munich O III filter
FILT_503_5+86	Munich O III filter redshifted by 1800 km/s

Table 2.3: Exchangeable filter set. All these will go in Wheel 4 or 5. Corresponding wavelengths are available in Appendix B.2.

2.3.3 User Provided Filters

The installation of user provided filters in FORS2 is subject of approval by the Director of Paranal and will only be considered upon recommendation of the ESO program committees (OPC and DDTC). The filters and their mounts must comply optically and mechanically with the specifications of the standard FORS2 filters and mounts (which can be requested from ESO via the Instrument Operation Team; email: fors2@eso.org).

The diameter of user provided filters shall not be smaller than 138mm (parallel beam) to avoid vignetting which would be equivalent to a reduction of the main mirror diameter. Interference filters (115±0.25mm) are used in the converging beam of the camera. Their spectral resolution shall not exceed 100 (SR mode) or 400 (HR mode). There is a limited number of filter mounts (for converging beam filters only) available to be sent to the users on request.

The filters, fully assembled in the mounts, must be made available to the Paranal Observatory at the latest 6 weeks before the start of the respective observing program execution. They will be installed in the instrument and tested for compatibility and focusing during this time. The Observatory reserves the right not to allow special filters to be mounted for observations in case of technical and/or operational problems. User provided filters are usually not allowed for FORS2 service mode observing programs.

2.3.4 HR Collimator Field Stop

For HR observations in imaging mode the MOS slit arms are also used to form a field stop mask to limit the field in the focal area of the instrument and thus to reduce stray light.

2.3.5 Occulting Masks

Individual arms of the MOS unit can be used in the direct imaging modes (this includes also imaging polarimetry) to block light from bright objects next to very faint ones. In this case, the use of the FIMS software tool is mandatory for the preparation of the observations; for details see the FORS FIMS Manual.

2.3.6 Image Motion due to Flexure

Image motion due to instrument flexure under gravity is below 0.25 pixel over a 1 hour exposure with the standard and a 2 hour exposure with the high resolution collimator for zenith distances less then 60°.

2.4 Spectroscopy

Spectroscopy Modes: FORS2 offers four spectroscopic observation modes: LSS, (P)MOS, MXU, and HIT.

A variety of grisms with different wavelength ranges and dispersions is available (see Table 2.4). The grisms can be combined with filters for order separation or more specialized settings. The dispersion direction is along the X direction of the CCD in all spectroscopic modes with the exception of the HIT mode, where a dedicated grism that has been rotated through 90 degrees is used. The camera focus is set automatically depending on the grism-filter combination in the optical path of the instrument.

Usable Field for Spectroscopy: for objects close to the edge of the field of view (in the direction of dispersion), a part of the spectrum will not reach the CCD. Therefore, the typical usable field of view for spectroscopy with the standard and high resolution collimators will be reduced in dispersion direction.

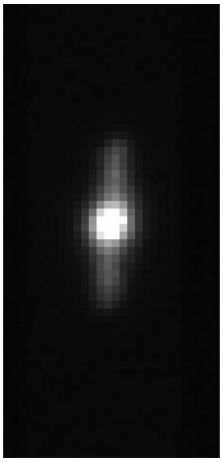


Figure 2.4: Superposition of two images taken before (round star) the application of the 6″ virtual slit and after (elongated star).

Virtual slit: Since January 2014, a "Virtual Slit" was commissioned at the Unit Telescope 1 and can thus be used with FORS2 (Fig. 2.4). This virtual slit is making use of the telescope's active optics to produce and keep elongated stars of given length (up to 6″) and orientation. Such elongated star can be put along the slit when using LSS, so as to put more flux in the slit. This has proven useful for the precise study of very bright stars. This mode is only available in Visitor Mode.

2.4.1 Grisms and Order Sorting Filters

Normal Grisms: a set of normal grisms is available which cover the full operational wavelength range of FORS2 with essentially three different resolutions: 230 Å/mm, 110 Å/mm, 45 to 50 Å/mm (see Table 2.4). All grisms are mounted in the grism or Wollaston wheels of the parallel beam section. Because of difference in sizes, grisms that go in the Wollaston wheel cannot go in the grism wheel, and vice-versa. This is particularly important for polarimetry or in choosing which grisms to use at a given time. Please note that, for operational reasons, some grisms are only available in visitor mode (see Table 2.4). Among these, GRIS_600V+94 and GRIS_200I+28 only go in the Wollaston wheel and so cannot be used for polarimetry. GRIS_1200g+96, GRIS_600R+14, and GRIS_600I+29 only go in the grism wheel.

Holographic Grisms: in addition to the normal/standard grisms some medium resolution high throughput grisms are available with FORS2: GRIS_1400V+18, GRIS_1200B+97, GRIS_1200R+93, GRIS_1200g+96, GRIS_1028z+29, GRIS_600RI+19 and GRIS_600z+23. These grisms are based on volume-phased holographic gratings which are cemented between two glass prisms (see Figures C.1 for the 1st order throughput measurements).

A special note about grisms 600RI and 1400V: Due to manufacturing errors, a tilt of the light beam is induced for grisms GRIS_1400V+18 and GRIS_600RI+19 which shifts the spectrum on the detector in Y direction by ∼111 and ∼272 pixels (unbinned 15 micron pixels, as compared to the object position in the through-slit image). There should be no part of the spectrum lost for grism 1400V since the CCD mosaics are large enough to receive all the tilted light. For grism GRIS_600RI+19 the expected consequences will be that the uppermost 21 arc-seconds of the field of view will fall off the CCDs in SR-mode.

Order Separation Filters: order sorting filters are available to allow for the suppression of spectral order overlaps in the spectra. Order separation filters are installed in the broadband filter wheel. Please note that some grisms can only be used with an associated order-sorting filter: GRIS_600I and OG590, GRIS_600R and GG435, GRIS_600RI and GG435, GRIS_600V and GG435, GRIS_600z and OG590, GRIS_1028z and OG590, GRIS_1200R and GG435.

Other FORS2 Filters: normal broad-band, medium and narrow-band filters can also be combined with the grisms, but only one filter at a given time and only filters which are not mounted in the same wheel as the user selected grism. Please note that such set-ups are not covered by the FORS Calibration Plan, see Section 4.1 for details.

Grism and Filter Transmission: efficiency curves of the available grisms are presented in Appendix C. For the filter characteristics see Appendix B.

2.4.2 Relative Astrometric Accuracy Requirements for Spectroscopy

Highly accurate relative astrometry is required for any observing mode which will make use of FIMS or blind offset acquisitions. The mask preparation with FIMS requires input images which are astrometrically corrected within the definitions and precision given below. DSS images will, in almost all cases, not be suitable for the task. In general the relative astrometry must be known better than 1/6 of the slit widths all over the field of view. Relative astrometry here means that the slit positions must be known relative to those of reference stars in the field of view with the given precision. To achieve such an astrometric calibration based on stars in your field is difficult. It is recommended to cross check the values for the image scale and field distortion in other fields (whenever possible in fields with astrometric standard stars[1]).

All these relative astrometric calibrations are not required, if your FIMS preparation is based on pre-images taken with any of the FORS instruments. It is strongly recommended to search in the VLT Science Archive (`http://archive.eso.org`) for released FORS imaging data.

Restrictions for pre-images to be used for the mask preparations: The target acquisition procedures were reviewed and based on the latest astrometric measurements there should be no more restrictions in using FORS1, FORS2 and other astrometrically corrected images (with world coordinate systems defined in the fits headers) to prepare masks for FORS2. The image scale of FORS1 images taken before March 22, 2003 would need to be corrected in the FITS headers, before usage. This can be checked with a few 2MASS or UCAC2 stars to verify the image scale in the center of the field of view. This should be discussed with the observatory

[1] see eg. UCAC1, Zacharias et al. 2000, AJ 120, p2131 or SDSS, Stoughton et al. 2002, AJ 123, p485

staff (usd-help@eso.org) before submitting the respective masks.

2.4.3 Instrument Flexures

The image motion due to instrument flexure under gravity is less than 0.2 unbinned pixels over a 1 hour exposure with the standard and a 2 hour exposure with the high resolution collimator for zenith distances less than 60°. Arcs and flats are however taken at daytime and at the zenith. This will introduce an offset between night time calibration based on telluric emission lines and day time calibrations based on arc lines depending on the zenith distance and the absolute angle of the Cassegrain rotator. The passive flexure compensation of the FORS instruments, based on support struts on the camera section was optimized down to the following small but not negligible image motions between zenith and the given zenith distances:

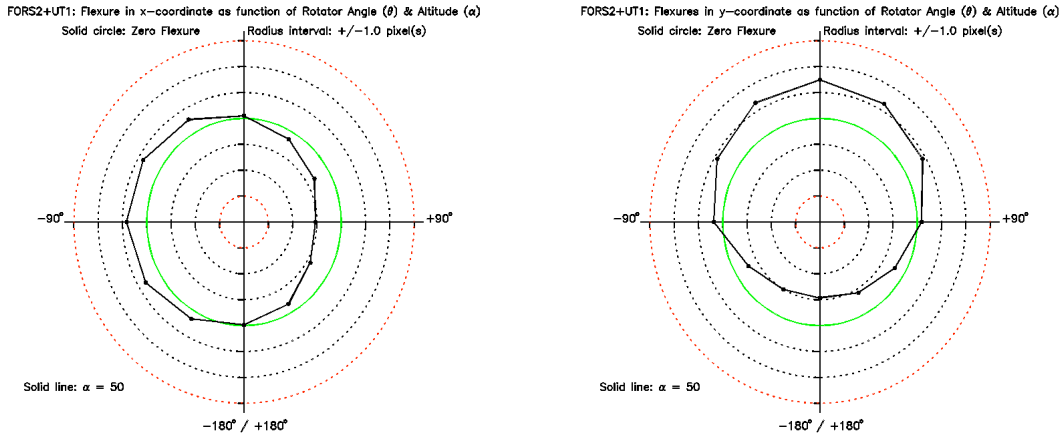

FORS2+UT1: Flexure in x−coordinate as function of Rotator Angle (θ) & Altitude (α)
Solid circle: Zero Flexure
Radius interval: +/−1.0 pixel(s)
−90°
+90°
Solid line: α = 50
−180° / +180°
FORS2+UT1: Flexures in y−coordinate as function of Rotator Angle (θ) & Altitude (α)
Solid circle: Zero Flexure
Radius interval: +/−1.0 pixel(s)
−90°
+90°
Solid line: α = 50
−180° / +180°

Figure 2.5: Results of flexure measurements as a function of the rotator position for the SR collimator at zenith distance of 40°. The panels show the flexure in *unbinned* pixels across (X) and along (Y) the slit. The solid green circle represents zero-flexure.

zenith distance	COLL_SR	COLL_HR
0°		
15°	<0.″06	<0.″03
30°	<0.″10	<0.″05
45°	<0.″14	<0.″07
60°	<0.″18	<0.″09

In all standard configurations telluric emission lines will fall into the wavelength range of FORS2, which allow to correct for any shifts/rotation between science and calibration observations. However, when using the 1200B+97 grism there may be no telluric lines in the observed spectra. The same is true for the 600B+22 or 1400V+18 grisms with MOS blades located towards the right/red side of the instrument. In the case of the MOS mode observations, adding empty slitlets at the top and bottom of the mask, which contain a wavelength range including 5577 Å, can be helpful.

Shifts and/or rotations between science observations of the same mask during the night cannot be corrected using sky lines. In this case the through-slit image can allow to look for potential movements of targets. If high precision is required (e.g., for radial velocity studies, line width determinations, abundance analyses) it is recommended to take a through-slit image before and after each science observation.

2.4.4 Longslit Spectroscopy — LSS mode

Longslit Mask LSS: A mask providing 9 longslits with high quality slit edges is available for the focal area of FORS2; they have a common slit length of 6.′8 (in SR mode) and fixed slit widths. The approximate offsets of the slits with respect to the central (0.″28) slit are given in Table 2.5. They are shown in terms of offsets on the sky as well as on the CCD (collimator dependent). The requested slit for an observation is selected by a decker mask. See Appendix E.2 for the orientation. The actual LSS slit positions on the CCD depend also

Grism	$\lambda_{central}$ [Å]	λ_{range} [Å]	dispersion [Å/mm]/[Å/pixel]	$\lambda/\Delta\lambda$ at $\lambda_{central}$	filter
FORS2 standard grisms					
GRIS_1200B+97 (5)	4350	3660 - 5110	24.0/0.36	1420	
GRIS_1400V+18 (3,5)	5200	4560 - 5860	20.8/0.31	2100	
GRIS_1200R+93 (5)	6500	5750 - 7310	25.0/0.38	2140	GG435+81
GRIS_1028z+29 (5)	8600	7730 - 9480	28.3/0.42	2560	OG590+32
GRIS_600B+22	4650	3300 - 6210	50/0.75	780	
GRIS_600RI+19 (3,5)	6780	5120 - 8450	55/0.83	1000	GG435+81
GRIS_600z+23 (5)	9010	7370 - 10700	54/0.81	1390	OG590+32
GRIS_300V+10 (1)	5900	3300 - (6600)	112/1.68	440	
GRIS_300V+10	5900	4450 - (8700)	112/1.68	440	GG435+81
GRIS_300I+11	8600	6000 - 11000	108/1.62	660	OG590+32
GRIS_150I+27 (1)	7200	3300 - (6600)	230/3.45	260	
GRIS_150I+27 (1)	7200	4450 - (8700)	230/3.45	260	GG435+81
GRIS_150I+27	7200	6000 - 11000	230/3.45	260	OG590+32
other FORS2 grisms (only available in Visitor Mode)					
GRIS_1200g+96 (4,5)	4880	4170 - 5640	24.3/0.36	1605	
GRIS_600V+94 (4)	5850	4430 - 7370	49/0.74	990	GG435+81
GRIS_600R+14 (4)	6270	5010 - 7690	45/0.68	1160	GG435+81
GRIS_600I+25 (4)	7950	6630 - 9390	44/0.66	1500	OG590+32
GRIS_200I+28 (2,4)	7450	5600 - 11000	162/2.43	380	

Table 2.4: Characteristics of the FORS2 grisms. The table lists the resolution $\lambda/\Delta\lambda$ achieved for a 1″ slit in case of the standard resolution collimator and for a 0.5″ slit in the case of the high resolution collimator at the given central wavelength in column 2. The wavelength range corresponds to a slit which is located in the field center (see Table 2.5 for long slit x-offsets). A value in parenthesis indicates the approximate wavelength at which order overlap occurs. Off-center slit positions (for instance with MOS, MXU or other LSS longslits) shift the wavelength range on the CCD accordingly.

(1) The start wavelength of the 2nd order overlap is given in parenthesis.

(2) An order separation filter (OG550) is cemented to the grism itself.

(3) This grism produces a Y offset on the CCD, see Section 2.4.1 for details.

(4) This grism is not part of the Standard Instrument Configuration and is therefore not available in service mode.

(5) These are higher throughput volume phased holographic grisms.

on the mounting reproducibility of the CCD dewar and may change slightly when the CCD dewar is mounted back to the instrument after maintenance (typically a few times per year) and following Visitor Mode runs with the auxiliary E2V detector. However, the centering accuracy of the objects on the slits is not affected by these variations in the projected slit positions.

Longslits of FORS2			
slit width	slit offsets	FORS2 in 15 μm pixels	
	sky	CCD SR-mode	CCD HR-mode
2.″5	45.″3	-362	-723
1.″60	34.″0	-272	-544
1.″0	22.″6	-182	-362
0.″51	11.″3	-91	-182
0.″28	0.″0	0	0
0.″40	-11.″3	91	182
0.″70	-22.″6	182	362
1.″31	-34.″0	272	544
2.″0	-45.″3	362	723

Table 2.5: Slit widths of the FORS2 longslits and approximate offsets relative to the central slit (in pixels on the CCD). The exact values are determined after each dismounting of the Cryostat (CCD).

Target Acquisition on Slit: target acquisition on the LSS mask slit can be done in the following ways:

1. in case of fairly bright objects, the "fast" mode acquisition can be used. This involves the operator selecting one or two targets on a direct image of the target field so that they are in the slit.
2. for faint sources the acquisition should be done with blind offsets - the offsets will be executed after centering on a reference star in the method above and verification in the subsequent image of the slit (template FORS2_lss_obs_slit_fast).

2.4.5 Multi-Object Spectroscopy with Movable Slitlets — MOS Mode

MOS Concept: in the MOS mode up to 19 objects can be observed simultaneously by means of slitlets which are formed each by two blades mounted on opposite carriers. The slitlets can be moved by linear guides to any position along the dispersion direction in the field of view. The slit width of the single MOS slits can be adjusted to any user defined value. By combining the linear positioning of the slitlets in the focal area with a rotation of the FORS2 instrument around its optical axis a wide variety of object configurations can be realized.

MOS Slitlets: 19 movable slitlets are available. Even-numbered slitlets are 20″ long[2], odd-numbered slitlets 22″ (projected on the sky). The approximate Y-position within which objects should be positioned is slightly decreased by parasitic light falling between the slitlets.

Collimator Constraints: the LSS mode is supported with both collimators but the MOS mode is only supported with the standard resolution collimator.

Target Acquisition with MOS: MOS observations must be prepared using the `FIMS` software (see the FIMS manual for more details). Reference stars are used to position the telescope and instrument such that the spectroscopy targets are in the slitlets of the predefined MOS mask.

2.4.6 Wide Slit Spectro-Photometry — SPECPHOT mode

For high accuracy spectro-photometry a supplementary mode SPECPHOT was introduced which is used mostly for the monitoring of the instrument response in the framework of the FORS calibration plan. The MOS slits are opened to 5 arcsecs slit width. By default the slits will be placed to the center of the field in dispersion direction. Alternatively, the slits can be set to the position of the FORS2 longslits or to any user defined offset position to the edge of the field of view (see the FORS2 Template Manual for further details).

[2]The reason is alternating light traps which prevent sky light from falling between the slit blade carriers

2.4.7 Multi-Object Spectroscopy with masks — MXU mode

FORS2 has a Mask eXchange Unit (MXU) built into its top section. This MXU is a magazine holding up to 10 masks (made of black painted stress relieved invar sheets of 0.21 mm thickness) laser-cut by the Mask Manufacturing Unit (MMU) of the VIMOS instrument. The purpose of the MXU mode is to allow more objects to be observed simultaneously than with the 19 slitlets MOS unit. Furthermore, it gives more freedom in choosing the location, size and shape of individual slitlets. As for MOS, MXU spectroscopy is only offered in the standard resolution mode of FORS2.

It is recommended that observers in Visitor Mode prepare the masks design or get familiar with MXU mask preparation before their arrival on Paranal (usually 3 days before the start of their observation run). Mask manufacturing and installation is only done at day time. Therefore, the mask manufacturing has to be initiated one day before starting the observations. Only up to 10 masks can be stored in the magazine and observed in one night.

MXU Slits: boundary conditions for the MXU slits are:

1. slit width: $0\farcs1$ (minimum) to $30''$
2. slit length: up to $30''$
3. available field of view:
   X: minus 15mm at either end; this is indicated by FIMS.
   Y: full field of view
4. slit shapes: rectangular, circular, and curved slits.

Acquisition Accuracy: With the improved astrometry of FORS2 with the MIT CCDs, the targets can be properly placed on the slits all over the unvignetted field of view in standard resolution mode.

Collimator Constraints: Only observations with the SR collimator are supported.

Target Acquisition with MXU: The MXU mask design has to be prepared with FIMS. The alignment of the mask on the sky is done with user defined reference stars and with pre-defined reference slits on the bottom of the upper CCD.

2.4.8 Slitless Spectroscopy

Slitless spectroscopy can be performed in MOS mode with all slits open. Please note that the sky background will be the same as for imaging mode observations and jitter offsets between the exposures must be applied to achieve a good sky subtraction.

For the preparation of observations in slitless spectroscopy a very good understanding of the instrument optics is essential: Note that the 0th order of grisms 150I and 200I will fall into the field of view of FORS2 and contaminate 1260 and 480 unvignetted pixels on the left/blue side of the field of view of FORS2 (unbinned 15 μm pixels). Any observation with filters of wavelengths which are off the central wavelength of the grism will cause field vignetting which can cut the field on both sides depending on the sign of the wavelength offset between filter and grism. Depending on the length of the spectra (the requested filter) the targets should be more than half the length of spectra off the zero order and the field vignetting!

2.5 Polarimetry with FORS2

Polarimetry Concept: the polarimetric modes allow the measurement of linear and circular polarization, both for direct imaging and spectroscopy. The polarization optics are located in the parallel beam section and consists of a Wollaston prism as beam splitting analyser and two superachromatic phase retarder plate mosaics (9 individual plates arranged in a square mosaic frame) to measure linear and circular polarization. Both mosaics are installed in rotatable mountings on a dedicated swing arm which can be moved in and out of the light path. The Wollaston prism is inserted in the uppermost wheel of the parallel beam section.

Collimator Constraints: polarimetry with FORS2 is only possible with the SR collimator.

2.5.1 Imaging Polarimetry — IPOL mode

Strip Mask for Imaging Polarimetry IPOL: for imaging polarimetry (IPOL) of extended objects or crowded fields a strip mask is inserted in the focal area of FORS2 to avoid overlapping of the two beams of polarized light on the CCD. When using the standard resolution collimator, the strip mask is formed by placing every second MOS slit jaw carrier arm (odd numbered MOS slits) across the field of view of the instrument. A full coverage of the imaging field of view is then achieved by taking two frames displaced by 22″ in direction of the MOS slitlets.

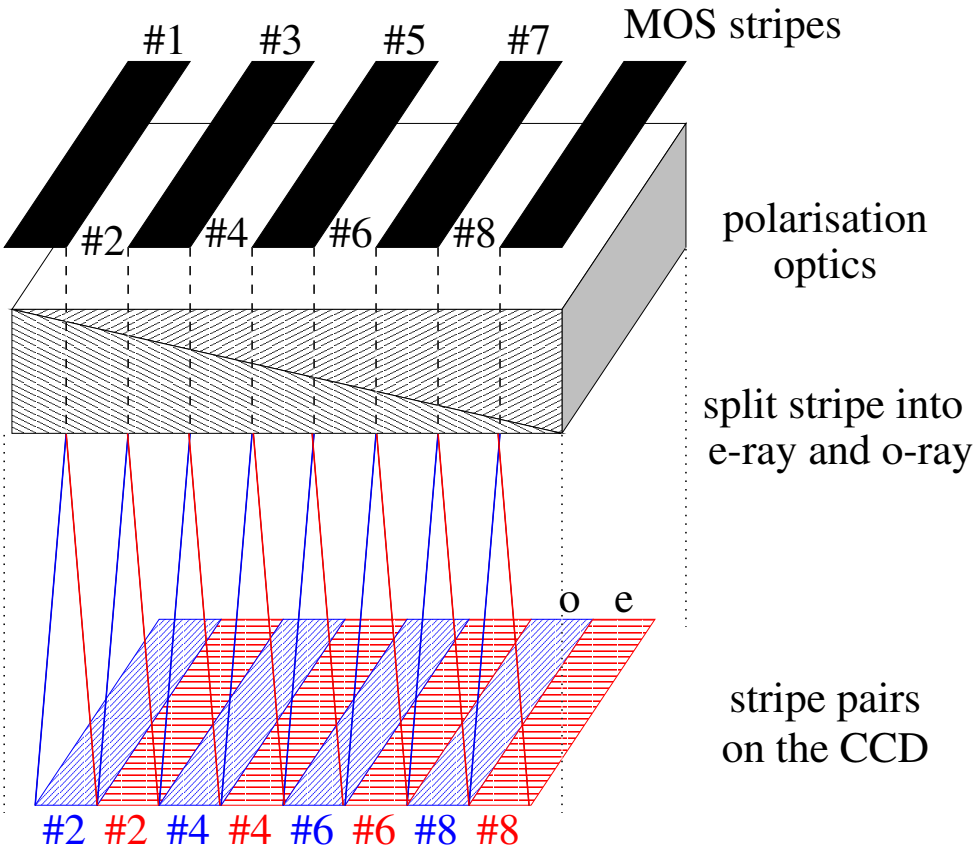


Figure 2.6: For imaging polarimetry (IPOL) of extended objects or crowded fields a strip mask is inserted in the focal area of FORS2 to avoid overlapping of the two beams of polarized light (ordinary – o-ray – and extraordinary – e-ray – on the CCD.

Field Coverage: Since by design, in IPOL observations only half of the full field of view of the instrument is imaged on the CCD in one exposure, the complete field coverage can only be achieved by offsetting the telescope accordingly in between exposures. This procedure is not automatic and should be done by the user.

Retarder Plate Angles: The retarder plate angles can be selected from a set of fixed predefined angles (see Table 2.6).

Retarder Plate	Position Angles (deg)
circular	**-45, 45**, 135, 225
linear	**0, 22.5, 45, 67.5**, 90, 112.5, 135, 157.5
	180, 202.5, 225, 247.5, 270, 292.5, 315, 337.5

Table 2.6: The table lists the angles of the predefined retarder plate positions which can be selected for imaging and spectropolarimetry. To achieve the highest accuracy we recommend to take exposures with the highlighted plate position angles.

Filters for IPOL: All imaging filters (see Section B) can be used except the ones that are located in the Wollaston wheel in the instrument standard configuration (see Section 2.1). The use of the latter is in principle possible, but requires a reconfiguration of the instrument. This, however, is considered for visitor mode

observations only and needs a priori approval by the Observatory before proposal submission, as otherwise the proposal would not pass the feasibility stage.

Target Acquisition in IPOL: Only fast modes are available. In the fast mode the object is selected at the instrument console by mouse click in an acquisition image and the telescope is then offset such that the target is at the center field position of MOS slit 10. The FIMS tool can still be used (PMOS mode with all slits open) to simulate the focal field geometry in cases of rather complex target distribution.

2.5.2 Spectropolarimetry — PMOS mode

MOS Slit/Strip Mask for Spectropolarimetry PMOS: spectropolarimetry (PMOS) using MOS slitlets is possible with the standard resolution collimator only. In this mode the MOS slitlet arms with odd numbers are positioned to form the same strip mask as for imaging polarimetry. The even numbered slitlets are available as in the normal MOS mode, i.e. they can be positioned on the objects in the field of view.

Slitless Spectropolarimetry: slitless spectropolarimetry can be implemented for SR collimator in a similar way as for MOS, but keeping the odd MOS slitlets in close position. See Section 2.4.8 for general comments on slitless spectroscopy.

Grisms and Filters for PMOS: all grisms (except GRIS_600z+23, GRIS_150I+27, GRIS_600RI+19, GRIS_600V+94, and GRIS_200I+28) together with the recommended order separation filters can be used in PMOS mode. The above mentioned grisms that may not be used are configured for the Wollaston wheel and can therefore not be mounted in the grism wheel. Other filters together with these grisms can be used if the filter is not mounted in the Wollaston wheel (see Section 2.1).

Retarder Plate Angles: the retarder plate angles can be selected from a set of fixed predefined angles (see Table 2.6).

Target Acquisition for PMOS: Fast and FIMS-based acquisition modes are available, but fast mode can only be applied for single target observations. Multi-object spectro-polarimetry will require mask preparation with the FIMS software. The fast mode will put the selected object on MOS slit 10 in the center of the field. The slit length is the standard 20″. The other MOS slits are set-up to the same position and slit width as slit 10 and can serve for sky background measurements. Blind offset acquisitions are supported.

2.5.3 Performance of the Polarimetric Modes

The polarization optics allow the determination of the degree of polarization to a relative error of $< 3 \times 10^{-4}$ and of the position angle (depending on the target polarization) to about 0.2°. For observation in the center of the field no instrumental polarization was found at the detection level of our measurement of $< 3 \times 10^{-4}$. For off-axis measurements (3 arminutes offset) spurious polarization of up to $\sim 8 \times 10^{-4}$ was detected in some measurements (circular polarization in this case).

Important updates on the instrumental polarization:

- When the polarization optics were mounted in FORS1, we found a strong linear instrumental polarization in the corners of the field of view. This spurious polarization field shows a high degree of axial symmetry and smoothly increases from less than 3x10^{-4} on the optical axis to 7x10^{-3} at a distance of 3 arcmin from it (V band). There is currently no data available in case of the other filters and spectro-polarimetric measurement. The corrective functions can be estimated with an observation of a globular cluster with the respective filters and details of such work can be found on the FORS webpage (http://www.eso.org/sci/facilities/paranal/instruments/fors/inst/pola.html). There was no problem for spectro-polarimetric or imaging polarimetry observations of single targets in the center of the field of view. In case of the circular polarization the spurious polarization was found to be an order of magnitude smaller.

  We intend to repeat the analysis for FORS2 and will report the results once they are known. We expect the results to be qualitatively the same for FORS2 as they were for FORS1.

- New tests confirm that cross-talk from linear to circular polarisation is present (confirming Bagnulo et al. 2009). Note that it appears only when one wants to measure a weak field of circular polarisation

in a source that is strongly linearly polarised. It is stronger in the blue ($\sim$ 10%, i.e., a signal of linear polarisation of the order of 10% is seen as a signal of circular polarisation of 1%) than in the red (in the R filter, it seems to be about 5%), but is not stable in time. The origin may be the LADC or the SR-collimator. Further tests are ongoing to analyse this.

2.6 High Time Resolution Modes

2.6.1 Overview

The principle of the high time-resolution (HIT) mode is to move the charges in positive x-direction on the CCD while integrating the incoming light with the exposure shutter open. The time resolved spectra or light curves are stored on the CCD which is then read out at the end of the sequence with the mode of lowest read out noise (100kHz,2x2,high).

The HIT mode allows imaging observations of one or more targets (HIT-I), as well as spectroscopic observations of up to two targets (HIT-S or HIT-MS). The imaging mode uses the MOS to create a pseudo-longslit on the extreme left-hand side of the unvignetted field of view, whereas the spectroscopic mode uses pre-defined (in the case of HIT-S mode) or user-defined (in the case of the HIT-MS mode) masks installed in the FORS2 mask exchange unit (MXU). The position angle of the instrument can be selected such that a second target may be observed simultaneously in the HIT-MS mode, and two or more in the imaging mode. Please note that the HIT mode observations are only configured for the standard resolution collimator COLL_SR.

One shift mode denotes that the charges are moved at constant speed on the detector until the complete detector is used as storage for the data. A part of the FORS2 MIT detector mosaic is vignetted by the FORS2 top unit. Therefore not all 4096 columns can be used to store the data, but only 3548 columns. The charges are moved over this number of columns in the user specified times of 1, 4, 16, 64, or 256 seconds. The resulting frequencies of 0.28 to 73 pixels/millisecond are not, however, the effective time resolution; the time resolution is reduced by the seeing (in the case of a wide slit) or the slit width in units of pixels. This corresponds to the number of shifts a pixel remains in the exposed region for. For an image scale of $0\farcs125$/px and a seeing of $1''$ the time resolutions would be between 2.3 milliseconds and 0.56 seconds for the fastest and slowest modes respectively.

HIT mode name	one-shift time	time resolution
HIT-OS1-1sec	1s	0.0023s/$''$
HIT-OS2-4sec	4s	
HIT-OS3-16sec	16s	
HIT-OS4-64sec	64s	
HIT-OS5-256sec	256s	0.56s/$''$

Table 2.7: Available HIT reading speeds.

The readout mode (100kHz,2x2,high) was selected to give the lowest possible readout noise level. All frames will be binned at readout time. The CCD parameters like the binning are deeply hidden in the CCD configuration file and cannot be changed during normal operation. About 40 seconds overhead time is expected to readout the full mosaic detector and to handle the data files.

The fundamental problem with the HIT-I and HIT-S modes is that even the smallest image motions due to atmospheric effects or residual guiding offsets will strongly compromise the photometric accuracy of the measurements when used in conjunction with a wide-slit. The respective targets will appear brighter while the residual image motion is in direction of the moving charges on the CCD. High accuracy photometry can not be done with the HIT modes unless a nearby star can be used as a reference source!

2.6.2 High Time Resolution Mode – Imaging (HIT-I)

The MOS slits will be placed to the extreme left side (-3 arcminutes offset from the centre of the field) and opened to a user defined (typically broad) slit width. The mode (HIT-I) can be used with any available FORS2 filter of the FORS2 standard configuration and the exchangeable interference filters. Accurate photometry on

a 1% level is only possible if there is a nearby star observed simultanously on the slit as a flux reference. Another requirement is to select a slitwidth which is larger than the actual seeing. The residual guiding offsets would reduce the performance to about the 10% level, without the differential measurement of a reference star. The atmospheric effects on the image motion would be only corrected in case of a reference star within the isoplanatic angle. This effect is however thought to be relatively small for large telescopes.

2.6.3 High Time Resolution Mode – Spectroscopy (HIT-S)

The readout direction for FORS2 is in the spectral direction for the standard FORS2 grisms. Only the cross-disperser grisms XGRIS_600B and XGRIS_300I can be used for the HIT-S mode. There are 7 masks available with slit widths between 0.5 and 5 arcseconds. The absolute photometric accuracy will be poor, since it is not possible to do a differential photometric measurement with a 2nd star on a slit. Equivalent widths of lines and for a wide slit also the colours should be less compromised by the image motion. As for the imaging mode, the slits are on the extreme left side of the field of view, offset by about -3 arcminutes from the center. The slits are little squares. The grism XGRIS_300I can be used with order separation filter OG590 or without. In the later case there would be some 2nd order overlap typically at the red end of the 1st order where the CCD response would be reduced. The 2nd order overlap would start at >6600Å but would become important at wavelengths above about >8000Å depending on the colour of the target. The following slit masks are available:

mask name	slit width
HITS_0_5+900015	$0.5''$
HITS_0_7+900016	$0.7''$
HITS_1_0+900017	$1.0''$
HITS_1_3+900018	$1.3''$
HITS_1_6+900019	$1.6''$
HITS_2_0+900020	$2.0''$
HITS_5_0+900021	$5.0''$

The respective rotated grisms are identical copies to the standard FORS2 grisms (600B, 300I). The wavelength range of the grisms are however slightly different from the standard ones. This is primarily caused by the asymmetric mount of the FORS2 MIT CCD mosaic which is off-centered by $33''$.

FORS2 cross disperser grisms for the HIT-S mode

Grism	$\lambda_{\rm central}$ [Å]	$\lambda_{\rm range}$ [Å]	dispersion [Å/mm]/[Å/pixel]	$\lambda/\Delta\lambda$ at $\lambda_{\rm central}$	filter
XGRIS_600B+92	4452	3300 - 6012	50/0.75	780	
XGRIS_300I+91	8575	6000 - 11000	108/1.62	660	OG590+32
XGRIS_300I+91	8575	5032 - (6600)	108/1.62	660	

The central wavelength is defined as the wavelength $\lambda_{\rm central}$ in the center of the field of view. The gap between the two CCDs will cause a gap of about 7 pixels in the spectra at a wavelength of approximately $\lambda_{\rm central} - 267\,\text{pixels} \times$ dispersion.

2.6.4 High Time Resolution Mode – Multiple-Shift Mode (HIT-MS)

A multiple-shift (MS) mode is also available. This mode is predominantly implemented for fast spectroscopy and allows a block of rows to be shifted together, rather than a single row as is the case with the previously implemented one-shift (OS) mode. In the MS mode, two user-defined slits can be used (with a mask manufactured for the MXU) which place the spectra of the target and a comparison star (for slit loss determination) onto a small region of the CCD. After a pre-defined "wait" time, the rows of the CCD are rapidly (in ∼50 microseconds) shifted, causing the exposed region to be moved into the "storage area" (the unexposed region) of the CCD and a new region to be illuminated. This "shift and wait" scheme continues until the first pair of spectra taken reach the limit of the storage region and the CCD is subsequently read-out in the normal way.

This HIT-MS mode is offered in visitor mode with either the MIT or E2V mosaics. It is offered with two $5''$ long slits (allowing 41 pairs of spectra per CCD readout), or a single $10''$ long slit and a user-defined slit-width. The position angle of the rotator is determined so that the target and comparison slits fall onto adjacent x-pixels on the CCD. The y-pixel positions of the two slits are determined by the offset between the

target and the comparison star. This offset also determines the relative spectral coverage of the two spectra. Offsets in the range $5'' - 300''$ are possible, but it is recommended to choose a comparison with a separation of $<60''$ to ensure a reasonable flux calibration.

Visitor mode only! The cross disperser grisms are not included in the FORS2 standard configuration. There will be no instrument setup changes according to the service mode rules and accordingly the spectroscopic HIT-S and HIT-MS modes are only offered in visitor mode! (HIT-I - imaging mode is offered both in visitor and service mode).

2.6.5 OB-preparation

The HIT mode templates for modes HIT-I and HIT-S are of "fast mode target acquisition" type, whereas the HIT-MS mode is fims based. There is no mask preparation required for the phase 2 observation block (OB) preparation, except for the HIT-MS mode. There are special templates available for the modes: three observation templates for the night time science observations for target acquisitions, through slit images, and the science observation. Additionally, flat field templates for HIT-I, HIT-S, and HIT-MS mode and an arc line spectral template for HIT-S and HIT-MS modes.

For the HIT-I (imaging) mode the OB would consist of three templates in the following order:

FORS2_hiti_acq_fast	target acquisition
FORS2_hiti_obs_slit_fast	through slit image
FORS2_hiti_obs_exp_fast	science exposures

Very similarly in case of the HIT-S spectroscopic mode:

FORS2_hits_acq_fast	target acquisition
FORS2_hits_obs_slit_fast	through slit image
FORS2_hits_obs_exp_fast	science exposures

And finally in case of the HIT-MS spectroscopic mode:

FORS2_hitms_acq	target acquisition
FORS2_hitms_obs_slit	through slit image
FORS2_hitms_obs_exp	science exposures

2.6.6 Calibration plan

The bias frames of the normal spectroscopic modes can be also used for modes HIT-I, HIT-S and HIT-MS. This is not the case for flats fields and arcs of course, and for these specific frames need to be taken. The flat field frames and arcs should not depend on the selected readout speed. The observatory staff will define an appropriate readout speed for which well exposed calibration frames can be achieved. For the other readout speeds it is typically impossible to get the exposure level right. Night time standard stars are to be selected by the HIT mode users and the respective observation blocks are to be prepared by the users. In the case of the HIT-MS mode, a separate MXU mask will need to be prepared for the spectrophotometric standard.

2.6.7 Performance on the sky

HIT-S

The limiting magnitudes to reach a signal to noise ratio of $S/N = 5$ as obtained in every 2x2 binned pixels for the different grisms are given below. The value was calculated for the center of the wavelength range at dark time. The S/N drops strongly in the blue part of grism 600B. For the spectroscopic mode, the S/N is independent of the seeing for the very wide slit, but time resolution and spectral resolution would both become worse in case of a bad seeing. The limiting magnitudes for the slowest readout mode of 1024 seconds per one-shift are:

grism	limiting magnitude
XGRIS_600B	15.8
XGRIS_300I	15.9

The expected number of counts per binned pixels can be derived by the following equation, in the case of a 10th magnitude star[3], a dispersion of 0.75 Å pixel^{-1}, a response of ~ 0.17, and an OS-time of 256s:

$$\begin{aligned} \text{counts} &= \text{flux} * \pi * R^2 * \text{resp} * \text{disp} * \frac{\text{time}}{3548} * \text{bin}^2 && (2.1)\\ &= 1000 * 10^{-0.4*10} * \pi * 405^2 * 0.17 * 0.75 * \frac{256}{3548} * 2^2 && (2.2)\\ &= 1757 \text{ photons} && (2.3) \end{aligned}$$

HIT-I

In the case of the imaging modes, the number of parameters like the seeing, the night sky brightness, and the number of filters, is very high and it is hard to present a meaningful table with limiting magnitudes. The expected count rates integrated in the spatial direction (assuming no slit losses) for a filter width of 1115 Å are estimated by the following equation for a 15th magnitude star:

$$\begin{aligned} \text{counts} &= \text{flux} * \pi * R^2 * \text{resp} * \text{fwhm} * \frac{\text{time}}{3548} * \text{bin} && (2.4)\\ &= 1000 * 10^{-0.4*15} * \pi * 405^2 * 0.3 * 1115 * \frac{256}{3548} * 2 && (2.5)\\ &= 17288 \text{ photons} && (2.6) \end{aligned}$$

You may have to distribute the 17000 photons over the PSF and to divide with the gain factor of 0.7e$^-$/adu to estimate peak flux values and the integrated signal to noise ratio.

HIT-MS

Since the exposure time and slit width are free parameters, the limiting magnitude for the HIT-MS mode is the same as that for the traditional spectroscopic modes. The only difference is that the charge remain stored on the detector for longer and are therefore subject to correspondingly higher dark current and cosmic ray events. For this reason, the HIT-MS mode is best suited to short exposures, which would otherwise be impossible (or prohibitively expensive in terms of overheads).

2.7 Rapid Response Mode (RRM) for FORS2

The Rapid Response Mode (RRM) is offered for observations of transient phenomena such as gamma-ray bursts or supernovae in semi-automatic mode. The user (PI or Co-I of an approved target-of-opportunity program) submits an ftp file with the coordinates of the target to a specific ftp server on Paranal. A special program at the telescope continuously monitors this ftp directory; when it detects a file, it checks if the filename corresponds to an approved activation code, and if this is the case, the on-going observations are ended, and a new BOB starts an OB with the same name as the ftp file. The telescope automatically presets to the coordinates specified in the ftp file, and the requested observations are performed straight away.

PIs of approved FORS2 ToO programs requesting this mode need to prepare their OBs in the usual way. However, these RRM programs use specific acquisition templates described in the FORS Template Reference Guide, available at http://www.eso.org/sci/facilities/paranal/instruments/fors/docs. More information on the RRM can be found on the USD Phase 2 webpages at
http://www.eso.org/sci/observing/phase2/SMSpecial/RRMObservation.FORS.html

[3]The 1000 photons at 5500 Å for a 0th magnitude star is just a nice number to remember.

2.8 Detectors

2.8.1 General Properties

Chip Characteristics, Pixel Number and Size, CCD Control: The standard detector mosaic of FORS2 consists of two 2k×4k MIT CCDs (the pixel size is 15 × 15 μm), thinned and anti-reflection coated. The E2V mosaic, previously installed on FORS1, is a mosaic of two blue optimised 2k×4k E2V CCDs, with the same pixel size (15 × 15 μm). In both mosaics the detectors are flat and the bottom ('chip 2') detector is rotated and shifted with respect to the upper ('chip 1') detector. The most accurately determined values for this rotation and shift can be found in the header keywords for the respective detectors and they are summarised in Table 2.8.

Detector Mosaic	rotation (deg)	X-offset (μm)	Y-offset (μm)
MIT (red)	0.08	30.0	480.0
E2V (blue)	0.025	-10.5	1390

Table 2.8: The detector geometry of the two mosaic detectors.

The CCDs are controlled by FIERA controllers. The obvious difference between the detector mosaics is the response: for the MIT mosaic it is optimised for wavelengths > 600 nm (with low fringing level), while for the E2V mosaic the response is optimised for wavelengths < 550nm (especially below 450 nm). For this reason, users should consider carefully which detector is best suited to their scientific goals, remembering that the E2V detector is available in Visitor Mode only.

Read-out Modes: The default readout modes for both mosaics are 200kHz,2x2,low for imaging (2x2 binned, low gain mode read with 200kHz) and 100kHz,2x2,high for spectroscopy. For special applications such as high resolution imaging or deconvolution techniques the following modes are supported: 200kHz,1x1,low (Imaging) and 100kHz,1x1,high (Spectroscopy).

Standard Operation Modes of the CCDs: the following standard CCD set-ups are offered for service mode observations:

- 200kHz,2x2,low — direct imaging IMG, OCC and imaging polarimetry IPOL
- 100kHz,2x2,high — spectroscopy LSS, MOS, PMOS and MXU

Additional Operation Modes: the following CCD set-ups are available in service mode only with a pre-approved waiver:

- 200kHz,1x1,low — direct imaging IMG, OCC and IPOL
- 100kHz,1x1,high — spectroscopy LSS, MOS, PMOS and MXU

Visitor mode observations allow the full complement of CCD read-outs. However, it is strongly recommended to use the standard read-out modes whenever possible (for instance to benefit from the calibration data taken in the context of the FORS instrument calibration plan).

Window Read-out: window read-out is not supported with either mosaic.

Noise, Gain and Conversion Factors: the read-out noise (RON) and conversion factors (K) as measured on the site for all CCDs are given in Tables 2.9. Please note that low gain denotes high charge conversion factors K (in e^-/adu) and slightly higher readout noise. Pickup noise is clearly visible for the fast imaging modes and in some exposures of the slow spectroscopic mode with the MIT CCDs.

Linearity, Full Well Capacity, Dark Current etc.: some more characteristic data of the CCDs are given in Table 2.8.1. None of the CCDs will saturate before reaching the numerical truncation limits (65535 adu).

Read-out Speed and Times: The detectors readout speed are 200 kHz and 100 kHz for the imaging and spectroscopic modes with both E2V and MIT mosaic detectors. Approximate readout times for various modes are given in Table 2.11.

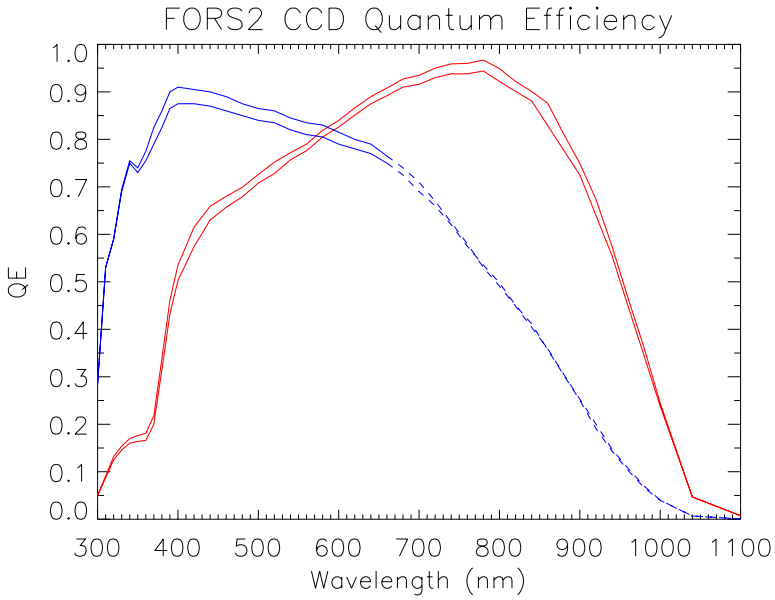


Figure 2.7: Quantum efficiency of the MIT (red) and E2V (blue) CCDs. The individual curves show the slight difference in QE of the two detectors in each mosaic. The dashed line shows where the fringing will limit the S/N achievable with the E2V detector.

		E2V CCDs mosaic		MIT CCDs mosaic	
CCD	read-out mode	RON [e^-]	K [e^-/ADU]	RON [e^-]	K [e^-/ADU]
chip1	low, 200kHz	5	2.24	2.7	1.25
chip2	low, 200kHz	5	2.60	3.6	1.25
chip1	high, 100kHz	3	0.55	2.9	0.70
chip2	high, 100kHz	3	0.60	3.15	0.70

Table 2.9: Detector readout noise and conversion factors.

2.8.2 Fringes

MIT CCDs: The amplitudes of the internal CCD fringes are strongly reduced with respect to the old Site and Tektronix CCDs and the E2V mosaic. For Bessel I imaging, fringes are hardly visible (circular fringes from the filters are, however, visible for I_BESS and R_SPECIAL filters). For z_Gunn imaging, the fringe amplitudes are below 1% and in the strongest telluric lines in spectroscopic modes fringe amplitudes were found to be of the order of 5% in the worst cases. The MIT mosaic is most suited for any observation $>$ 650 nm.

E2V CCDs: The fringe amplitude of the new E2V mosaic at $>$ 650 nm is much larger than for the MIT detector. The fringes will remain in the night sky background in imaging modes with filters of a central wavelength $>$ 650nm even after the flat fielding of the data. For the data reduction it will be required to subtract the scaled night sky background from the frames. In spectroscopic modes only a partial correction of the fringe can be obtained from the flat fielding. At wavelength >650nm, signal to noise ratio of >15 may not be obtained due to the residual of the fringe corrections. Sky subtraction at these wavelengths will require that the target is observed at offset positions (nodding on the slit). This will, however, not correct for the residual fringes in the extracted science spectra.

Jitter and nodding on the slit: It will be mandatory to use offset techniques (jitter images, nodding on the slit) to subtract the sky background at wavelengths greater ∼800 nm for spectroscopy and due to the detector cosmetics at any wavelength in imaging mode. The fringes are quite stable but depend on the spectrum of the

Parameter	E2V mosaic	MIT mosaic
photosensitive pixels ($n_{\rm chips} \times n_x \times n_y$)	2×4096×2048	2×4096×2048
pixel size (μm)	15	15
dark current at –120C (e^-/px/h)	5.9 ± 0.8, 4.5 ± 0.8	2.1 ± 0.4, 1.4 ± 0.7
linearity (up to full well; % RMS)	(0.03,−0.4) (0.8, 0)	(−0.9, −0.5) (1.8, 2.1)
cosmic ray rate (events/min/cm^2)	10.1±2.3, 8.2±1.4	7.7± 0.4, 8.1±0.5

Table 2.10: Basic characteristics of the FORS2 CCDs. The two values of the dark current refer to chip 1 (upper) and chip 2 (lower) of the mosaic. The linearity values are given as (chip1,chip2), and for high and low gain.

readout area	speed, binning, gain	total readout time	default mode for:
E2V mosaic			
2×4k×2k	100kHz,2x2,high	39s	spectroscopy
2×4k×2k	100kHz,1x1,high	78s	high spatial resolution spectroscopy
2×4k×2k	200kHz,2x2,low	28s	imaging
2×4k×2k	200kHz,1x1,low	56s	high resolution imaging
MIT mosaic			
2×4k×2k	100kHz,2x2,high	41s	spectroscopy
2×4k×2k	100kHz,1x1,high	82s	high spatial resolution spectroscopy
2×4k×2k	200kHz,2x2,low	31s	imaging
2×4k×2k	200kHz,1x1,low	62s	high resolution imaging

Table 2.11: Approximate CCD readout times in the different read-out modes. The read-out times include the overheads during the exposure execution (for CCD wiping, header compilation).

night sky which will be variable. To subtract a scaled master sky will give quite reasonable results even at z-band wavelengths where observations without jitter or nodding will be very hard to calibrate. Most applicants will observe fainter targets with 8m-class telescopes while the sky will be as bright as with any other telescope.

2.8.3 Shutter

FORS2 contains a rotating half-segment exposure shutter which guarantees uniform illumination of the CCD to the 1 % level or better for exposure times as short as 1 sec (the shortest possible exposure time is 0.25 sec).

2.9 The Calibration Units

FORS2 contains two sets of internal calibration lamp units in its top section. The light from a variety of calibration lamps is projected onto a calibration screen inside the telescope, located approximately 2.5 m above the instrument. All lamps can be switched on and off individually and in several combinations by means of calibration templates (see http://www.eso.org/sci/facilities/paranal/instruments/fors/docs). Blue and red flat field lamps as well as Neon and Argon arc lamps are installed in both calibration units. He and HgCd arc lamps are only installed in one of the two calibration units. A guide to approximate exposure times is given in Sections 4.4 and 4.5, a spectral atlas of the FORS2 spectral calibration lamps in Appendix D. The red internal flat field lamps (FlatRed+1 and FlatRed+2) cannot be used anymore after the installation of the external calibration units. The control electronics of the respective lamps is now used by the external units (see below).

External Calibration Units: The flatfield lamps in the old internal calibration units have produced parasitic light in MOS and LSS flatfield exposures. Therefore, new external calibration units (ECUs) have been installed which are located above the LADC in the Cassegrain tower. The new calibration units consist of two blue and two red lamps which are linked to the Cassegrain tower with a fiber bundle. One of each red and blue lamps will be projected into the fiber bundle in focus (high illumination level) while the other lamps are out of focus of the projection optics. Only one of the two red and one of the blue lamps can be used at a given time. The ECUs are the only calibration units used for spectroscopic flats fields. Actually, we use the faint red lamp together with the bright blue lamp such that there is a secondary peak in the flat field spectrum

which may appear odd at first view. **Nighttime Calibrations:** For technical reasons the arcs and flats are only taken at day time with the telescope, guide probe, LADC parked and the beam shutter (identical with the calibration screen) closed.

Chapter 3

Observing with FORS

All observations with FORS are done via "observing blocks" (OBs). OBs contain the target information and a small number of users selected "observing templates" depending on the observing mode. The users will fill out the parameter fields ("keywords") of the templates (e.g., grisms, filters, slits). All the preparations are done with the phase 2 proposal preparation tool p2pp. Furthermore, FORS2 masks will have to be prepared with the *FORS instrument mask simulator*, "FIMS". The detailed information for the observation preparation are given in the p2pp-manual, the FORS template manual and the FIMS-manual. The instructions how to retrieve the manuals from the WEB pages are given in Section 1.

The strategy behind (observing blocks and templates) is to prepare the observations well in advance to minimize any interactive steps during the observations (optimization and service mode compatibility). The execution of the OBs will be mostly automatic and the execution will be done by telescope and instrument operators or the staff astronomers. Direct interaction at execution time is needed only for the target identification and the quality control of the data or for real time decisions. In the following we summarize the steps from a successful application to the final access of the data.

The preparation of service mode observations will require special care, some more rules and recommendations, since unclear points in the service mode packages will significantly delay the execution of the project. The additional requirements and instructions for service mode observations are available on the web:

http://www.eso.org/sci/observing/phase2/SMGuidelines.FORS.html

3.1 Selecting the Observing Mode

The first step is to select the best observing mode according to the scientific needs. In some cases there will be a choice between, e.g., the MOS and MXU modes[1] and in this case the optimization of the strategy will start at this point. In most cases the observing modes will be pre-defined and only a limited number of observing templates are needed and have to be studied in detail, with the help of the FORS template manual.

3.2 Fast modes or FIMS mask preparation

All multi-object observations in modes MOS, MXU and PMOS will require the preparation of mask with FIMS. Occulting bar imaging and slitless spectroscopy is only supported with fims-based modes. Typically the mask design has to be ready before starting the preparation of the observing blocks.

Meanwhile all observations in modes IMG, IPOL and LSS are done without using FIMS – as well as single target observations in "PMOS" mode. For faint targets we support blind offset acquisition modes for all the fast modes (this is done with the through slit templates). The astrometric requirements are similar for blind fast acquisitions and FIMS acquisitions. In general, the OB execution in fast mode will not be much faster than the FIMS mode, but the OB preparation will be.

[1] for example to observe 10 targets well distributed over the FORS field of view

3.3 Selecting the Instrument Setups and Exposure Times

A good understanding of the instrument is required, before starting the preparation of the observing blocks. It is possible to define observing sequences which do not make any sense - both within FIMS and within p2pp. Inconsistencies should be eliminated by the user, although a cross check of the OBs will be done both in visitor and service mode by verification scripts or the staff astronomers. It should be one of the first steps to define the instrument setups (Chapter 2) and to calculate the exposure times with the exposure time calculator, available on the ESO web site.

3.4 OB-preparation — FIMS based modes

1. Get your pre-imaging data or other astrometrically corrected images (see Section 2.4.2).
2. Select the observing mode, the instrument setup and calculate the exposure times with the exposure time calculator.
3. Prepare your masks with the FIMS software and keep the output file with suffix `.fims` to reload the mask if needed and the output files with extensions `.p_targ`, `.p_focf` (and `.p_gbr` for MXU mode) for the OB preparation. These files will be saved by FIMS in directory `~/.fims/SET/`.
4. Make a hard-copy of the mask configuration within FIMS on which the reference stars and slits are well visible and a few hard-copies of the same masks with high magnification. This will be the typical set of finding charts needed at the end. Ideally, you should use the "Make Finding Chart" option in FIMS.
5. Prepare the observing blocks - a typical OB in imaging mode (with occulting bars “OCC mode”) will consist of two templates:

FORS2_img_acq_algn	target acquisition
FORS2_img_occ_crsplit	science exposure

or similar for imaging polarimetry:

FORS2_ipol_acq	target acquisition
FORS2_ipol_obs_off	science exposures

For all spectroscopic modes, a through-slit image is required to verify the proper centering of the target on the slit. For observing modes MOS, MXU, LSS, HIT-MS, or PMOS, the OB would typically consist of the following three templates:

FORS2_mos_acq	target acquisition
FORS2_mos_obs_slit	through slit image
FORS2_mos_obs_off	science exposures

Here the MOS mode is used as an example but there is an identical sequence of observing templates for the other spectroscopic modes.

In case you want special calibrations not included in the FORS calibration plan (Section 4.1), a calibration OB has to be prepared which would look like the following scheme (again for the MOS mode example):

FORS2_ima_cal_coll	collimator selection
FORS2_mos_cal_daycalib	screen flats & arcs

where the first template is only used to select the collimator. Make sure you select the same collimator for your science and your calibrations.

There are a few important points to be verified now:

1. Do not mix observing modes in one OB.
2. Make sure that all FIMS input files belong to the same mask – in general only one mask per OB is possible: the keyword INS.FIMS.NAME at the top of the p_focf, p_targ and p_gbr files must be identical.

3. Be sure that the requirement for reference stars (and reference slits in MXU mode) are fulfilled – the details about the reference star selection are explained in the FIMS manual.

3.5 OB-preparation — Fast modes

1. Get any imaging data and good target coordinates and very good astrometry in case of blind offset acquisitions (see Section 2.4.2) and prepare finding charts with targets, slit positions and reference stars for blind offset acquisitions.
2. Select the observing mode, the instrument setup and calculate the exposure times with the exposure time calculator.
3. Prepare the observing blocks – a typical OB in imaging mode (fast "IMG mode") will consist of two templates:

FORS2_img_acq	target acquisition
FORS2_img_obs_crsplit	science exposure

or similar for imaging polarimetry:

FORS2_ipol_acq_fast	target acquisition
FORS2_ipol_obs_off_fast	science exposures.

For all spectroscopic modes, a through-slit image is required to verify the proper position of the target on the slit. For fast observing modes LSS, SPECPHOT, HIT-I, or PMOS, the OB would typically consist of the following three templates:

FORS2_lss_acq_fast	target acquisition
FORS2_lss_obs_slit_fast	through slit image
FORS2_lss_obs_off_fast	science exposures

here for the LSS mode but very similarly for the other spectroscopic modes. For blind acquisitions in "fast" modes LSS, and PMOS the coordinates of the reference star will be required for the target acquisition. The offset from the reference star to the target will be executed from the through slit image template, after fine adjustment of the reference star on the slit.

In case that you ask for special calibrations not included in the FORS calibration plan (Section 4.1) a calibration OB has to be prepared which would look like the following scheme:

FORS2_ima_cal_coll	collimator selection
FORS2_lss_cal_daycalib	screen flats & arcs

where the first template is only used to select the collimator.

There are a few important points to be verified now:

1. Do not mix observing modes in one OB.
2. Make sure that the same slits are used in LSS mode for all templates within an OB.
3. Verify that the offsets for blind offset acquisitions are correct in size and sign.

3.6 Estimate execution time and optimizing overheads

In the following example in MOS mode we presumed that the reference stars for the target acquisition were bright enough to be seen in 5 seconds (FIMS mode or blind acquisition typically with broad band filters) and that there were some targets on the slits which can be seen in 60s on the through slit image which is ideally done without filters (atmospheric dispersion corrector!) or with a broad band filter (to reduce the sky brightness in case of the IR sensitive MIT detector). No further acquisition overheads are required for the

Telescope	
telescope preset	3 min
guide star acquisition	0.75 min
active optics	2 min
LADC resetting	1 min
Interactive Acquisition (excluding exposure time)	
one loop IMG(occulting)/IPOL	1.5 min per loop
one loop MOS/MXU/PMOS	2.0 min per loop
one loop LSS/HIT	1.5 min per loop
two loops through-slit exposure	2.0 min per loop
Instrument	
instrument setup	0.5 min
collimator exchange	4.5 min
retarder plate setup	1.0 min
Exposure	
integration time	user defined
E2V read-out 100kHz binned	39s
E2V read-out 200kHz binned	28s
E2V read-out 200kHz unbinned	56s
MIT read-out 100kHz binned	41s
MIT read-out 200kHz binned	31s
MIT read-out 200kHz unbinned	62s

Table 3.1: Operational overheads with FORS2 on the VLT. The through-slit exposure is typically executed twice. It is important to include the overhead times while preparing proposals and service mode observations packages.

imaging mode after the preset and the start of the active optics correction. There is in most cases no need to repeat the acquisition procedure in the spectroscopic modes. The through slit images taken with the targets on the slits typically have to be repeated in case of corrections of the order of 1 pixel. Two loops are required to verify safely that the targets are on the slits.

FORS2_mos_acq	
telescope preset	180s
guide star acquisition	45s
active optics (2 loops)	120s
acq. image integration time	5s
acquisition procedure	120s
FORS2_mos_obs_slit – 2 loops!	
instrument setup	30s
through slit integration time (2*60s)	120s
through slit image (2*120s)	240s
FORS2_mos_obs_off – NEXP = 1 & NOFF = 1	
instrument setup	30s
science integration (1*3000s)	3000s
100kHz,2x2 CCD readout (1*41s)	41s
all OB execution time	3931s

Table 3.2: Example of a MOS execution.

There would be an additional overhead of 270 seconds to exchange the collimators (but this setup is partly executed during the telescope preset and the guide star and active optics setup procedure). Further overheads of 60 seconds per template exist for the PMOS and IPOL science templates to setup the retarder plates. This is now the time to optimize the strategy and to estimate if all your OBs can be done in the limited number of nights or service mode hours!

FORS2_img_acq	
telescope preset	180s
guide star acquisition	45s
active optics (2 loops)	120s
FORS_img_obs_crsplit – NEXP = 1 & NOFF = 5	
instrument setup	30s
science integration (5*600s)	3000s
200kHz,2x2 CCD readout (5*31s)	155s
all OB execution time	3530s

Table 3.3: Example of an imaging OB execution.

3.7 Visitor Mode

3.7.1 The final package

The final package needed at the telescope will typically consist of:

- finding charts
- observing blocks
- the FIMS output files and the pre-imaging data on which the FIMS preparation was done (FIMS modes only)

In most cases the meteorological conditions will be fine, but there are also bad nights with bad seeing or clouds and sometimes strong wind which will come typically from the North. Visitors should thus always ensure to have an approved backup programme.

3.7.2 At the telescope

The telescope and instrument operation is done by ESO staff. A good finding chart and a close collaboration between staff and visiting astronomer is the fastest way to the slit. The incoming data will be displayed on real time displays which will allow only very basic assessment of the data and automatically transferred to an offline workstation with data reduction software packages (iraf, Midas and idl). The basic observing modes will be pipeline reduced but sky subtraction and target extraction has to be done interactively. The working environment is described on the Science Operation website: http://www.eso.org/sci/facilities/paranal/sciops/. At the end of the night an automatic procedure "calobBuilt" will be started which will create a complete calibration OB for all modes and setups used during the night. The calibration OB will be executed during the morning hours.

3.7.3 At the very end

After the observing run, the visiting astronomer will be able to download the data from the ESO Science Archive through the User Portal. Reduced data (no matter if pipeline or interactive reduction) are not part of the archive and the visitor is required to back-up any of these files should they be of any use.
Please send us your end of mission reports with evaluations and suggestions – available through your User Portal or from

http://www.eso.org/sci/facilities/paranal/sciops/EoM/

3.8 FORS and the Unit Telescopes

3.8.1 Guide Stars, Telescope Offsets

All FORS science observations will require a guide star in the unvignetted field of view of the telescope. The guide star is used for the alignment of the telescope relative to the guide star coordinates, for the wave front sensor of the active optics system and for fast off-axis guiding with typical tip-tilt corrections of the M2 greater than 20Hz.

The guide stars are automatically found from the GSC-2 catalog by the telescope control system (TCS) during the acquisition of the field. Due to the limits of the Cassegrain field of view and vignetting constraints for the FORS instruments, the optimum distance range for guide stars from the field center is 4 – 7.4 arcmin for the SR collimator and 2 – 7.4 arcmin for the HR collimator. Depending on the seeing, the guide star brightness should be between 10 – 13 mag.

For small telescope offsets (a few arcsec to a few arcmin), the telescope may keep the same guide star; otherwise, it will automatically try to find a new one. Whether or not such telescope offsets cause a change of the guide star, depends on the offset amplitude and direction and on the position of the original guide star in the field. If the guide star is kept during an offset, the offset accuracy will be better than 0.1 arcsec. If the guide star is changed, larger offset errors can be introduced by the uncertainties of the guide star positions.

3.8.2 Telescope and Instrument Focus

The telescope focus is automatically set by the active optics system. No intervention is required by the observer. Defocussing of the telescope is not possible during the observations, although in visitor mode, it is possible to request no active optics correction, which will result in very out of focus images. The instrument focus is corrected automatically for the different thickness of the various filters, for the grisms, collimator and for varying instrument temperature (autofocus). For user-provided filters (visitor mode only) the instrument focus will be determined by the observatory engineering and operations staff which requires the provision of these filters to the observatory at least 6 weeks before the scheduled observing run.

3.8.3 Instrument Rotation and Position Angle on the Sky

FORS can be rotated independently from the guide probe. The allowed range for rotator presets with FORS is -180 to +180 deg while the operational range with FORS is -270 to +270 deg. Please note that the rotator offset angle of the telescope is minus the position angle of the targets on the sky. The value “9999” can be used to set the position angle to the parallactic angle.

3.8.4 Atmospheric Dispersion Compensation

Atmospheric dispersion is partially compensated by a linear atmospheric dispersion compensator (LADC) which is built into the M1 cell of the telescope in front of the Cassegrain focus.[2] It is designed to maintain the intrinsic image quality of FORS for zenith distances between 0 and 45° and to significantly reduce the effects of the atmospheric dispersion at higher airmass. The LADC position is automatically set when the telescope is preset to the target position and can not be corrected during the exposure. It is recommended to reset the LADC after significant changes in airmass during long series of exposures. At zenith distance larger than 45 degree the LADC prisms remain however always at the maximum separation. Although placed in front of the polarization optics there are no negative impacts (instrumental polarization) for polarimetric measurements expected or known (but see Sec. 2.5.3).

The FORS2 LADC, which was suffering from a poor coating, was replaced by the one of FORS1 whose coating had been removed. This led to a gain in throughput of 0.1 (in the blue), 0.07 (in V), 0.05 (in R), and 0.04 (in I) magnitudes, due to a reduction of the scattering. A report presenting the prism exchange of the FORS2 LADC and its influence on precision time-resolved spectrophotometry, and more particularly in

[2]The LADC is described in G. Avila, G. Rupprecht, J. Beckers: Atmospheric Dispersion Correction for the FORS Focal Reducers at the ESO VLT, “Optical Telescopes of Today and Tomorrow”, A. Ardeberg (ed.), Proc. SPIE 2871, 1135 (1997)

the context of exoplanet transits, is available in the March issue of The Messenger. It is also available from http://arxiv.org/abs/1502.03172 .

Chapter 4

Calibrating and Reducing FORS2 Data

4.1 Calibration Plan

The VLT observatory aims at providing calibrations of the FORS instruments with an accuracy as listed in Table 4.1. Applicants have to request additional observation time including overheads if much higher accuracy is required than given below or if the mode is not supported by the calibration plan. In this case the respective observation blocks must be provided by the users.

The FORS Calibration Plan will ensure that ESO provides dark frames, biases, flat field frames and arc lamp spectra with the exceptions given below. Observations of standard stars in broad band filters are executed to obtain photometric zero points, atmospheric extinction coefficients and first order colour terms for the BVRI filters. For the other filters only one flux standard star close to airmass 1 is taken.

The calibration plan for imaging has been revised in October 2011, following the detailed simulations of Bramich et al. (2011). Their technical report (VLT-TRE-ESO-13112-5429, *FORS Zero Point Monitoring And Absolute Photometry*) concludes that it is possible to reach absolute photometric accuracies of 1.4–1.8% if: (a) two standard star images per night are taken as close together in time as possible, at airmasses between X $\approx$ 1.1 and 1.8, ensuring a range in airmass of $\sim$0.6 to 0.7; and if (b) at least 18 photometric nights are included in the photometric modeling of the data. Such strategy also enables the monitoring of the atmospheric extinction coefficient and of the colour term coefficient, to a precision of $\sim$6–8%, and $\sim$20–30% respectively. Additionally, standard stars are observed at the middle and end of the night whenever the night has been classified photometric (and science data requiring photometric data are observed), to assess the stability of the night. Nightly zeropoints and extinction coefficients are available at http://archive.eso.org/qc1/qc1_cgi?action=qc1_browse_table&table=fors2_photometry, and can be plotted from http://archive.eso.org/qc1/qc1_cgi?action=qc1_plot_table&table=fors2_photometry, while the description of the table entries and definitions can be found at http://www.eso.org/observing/dfo/quality/FORS2/qc/zeropoints/zeropoints.html. Due to the method used, the nightly zeropoints become available with a delay of about 4 weeks. Programs requiring photometric conditions might, however, want to submit one or several standard star OBs to be executed close in time to the science OB, to confirm the extinction stability on short time-scales. Note that a time-dependent illumination pattern was revealed in FORS images (Moehler et al. 2010, PASP, 122, 93), which prevents photometric accuracies better than 1% to be reached: for this reason standard star fields are being observed each time with different spatial offsets and rotation angles, with the aim of eventually finding an analytic correction to the illumination pattern.

Spectra of spectro-photometric standard stars with 5 arcsec slit width will provide response functions for the flux calibration of spectroscopic data. The standards for MOS and MXU spectroscopic modes are– observed with the MOS slits in the center of the field, while standards for long-slit spectroscopy are observed with the MOS slits at the position of the long slit. Of course the MOS or MXU slits of the science setups are not in the center of the field of view, therefore some parts of the spectra will not overlap with the derived response function. Please request special calibrations (send OBs) if this is problematic for your scientific data reduction.

Visitor mode observers are welcome to use calibration data taken in the framework of the FORS Calibration Plan. They should expect about half an hour per night to be used by observatory staff for calibration exposures. In most cases the staff will observe one field with photometric standards for the performance monitoring and

a spectro-photometric standard with a 5 arcsecs MOS slit for the setups used in the respective nights.

Archive users should note that standard stars taken several days into the future of a science observation will not always be "captured" by the association process and in such cases they will not be included in the data set delivered by *calSelector*. When this is the case users will need to manually search the archive themselves to find suitable standard stars.

The calibration plan does not support:

1. night time standard stars and twilight flats for non standard CCD-modes — as a baseline only the CCD read-out modes 200kHz,2x2,low (imaging) and 100kHz,2x2,high (spectroscopy) will be supported for FORS2.
2. any standard star observations to correct for telluric absorption lines
3. radial velocity standards
4. any day or night calibrations for slitless spectroscopy
5. any day or night calibrations for spectroscopy with filters other than the recommended order separation filters GG375, GG435, OG590 and FILT_465_250
6. any night time polarimetric calibrations for circular polarisation
7. any day or night time polarimetric calibrations for retarder plate angles different from 0,22.5,45,67.5 degree (linear)
8. any day time polarimetric calibrations for retarder plate angles different from -45,45 degree (circular polarimetry)
9. any PMOS screen flats at retarder plate angles different from 45.0 degrees
10. any IPOL screen flats
11. any IPOL day or night time calibrations with COLL_HR

The observatory staff will carry-out a day-time calibration OB in the morning with biases, screen flats and arc-lamp spectra for all spectroscopic and spectro-polarimetric setups. This is done with the semi-automatic calobBuilt software. Calibrations related to items 5 and 6 are hard to configure in an automatic tool and therefore not included in the calibration plan. Calibrations related to items 8 and 9 are thought to be not very useful for the data reduction and therefore not included. In all other cases the respective calibrations are not supported by the calibration plan to keep the time for the calibration plan within some reasonable limits. The daily maintenance activities of telescope and instruments must not be compromised by extensive calibration requests by visiting or staff astronomers. We will have to keep it as short as possible or the calibrations must be interrupted (postponed or even partly canceled) in case of scheduled or urgent maintenance and setup activities.

4.2 Image Field Distortion and Scales

The image distortion was measured on an astrometric standard star field in 47 Tuc (Tucholke 1992, A&AS 93, 293) for FORS1 and FORS2 and in the field of cluster Pal 3 for FORS2 (SDSS coordinates). This method is limited by the accuracy of the astrometric positions of the stars. The measurements were done with FORS1 in the Bessel V band. A third order polynomial was fitted to the measured data. The formulae to determine the deviation (in pixel) of the position measured on the detector from the real (astrometric) position (r in pixel) are given below. The measured distortion is in agreement with the design data (SR 0.30%, HR 1.55% at the corner of the field). The residuals of the fit were 0.05 pixels in SR and 0.06 pixels in HR mode.

FORS1 SR: $\Delta r = 2.091{*}10^{-9}{*}r^3$ - $1.228{*}10^{-6}{*}r^2$ + $0.360{*}10^{-3}{*}r$
FORS1 HR: $\Delta r = 9.515{*}10^{-9}{*}r^3$ - $3.605{*}10^{-6}{*}r^2$ + $1.001{*}10^{-3}{*}r$

The radial offset derived from the equations above has to be subtracted from the measured position on the CCD. The radius r is calculated from the reference pixel (fits keywords CRPIX1 and CRPIX2) of the world

Calibration Mode	Collimator	Frequency (4)	# of Exp	Time	Results	Accuracy
Bias		every 5d	5	Day	bias level, RON	RON/2
Darks		monthly	3	Day	dark current	
Screen Flats UBVRI	SR	every 4d	2	Day	CCD check	
Astrometry	SR+HR	annually	1	Night	distortion, scale	1 pixel
Imaging Sky Flats	SR	every 3d (1)	5	Twilight	normalized flat	2%
	HR	every 3d	5	Twilight	normalized flat	2%
BVRI photom. std	SR	nightly (1,2)	1	Night	zero points	<2%
					extinction coeff.	<8%
					colour coeff.	<30%
high airmass BVRI std	SR	as needed (1,2)	1	Night	zero points	<2%
					extinction coeff.	<8%
					colour coeff.	<30%
BVRI photom. std	HR	as needed (1,2)	1	Night	zero points	5%
Flux std Gunn & other filters	SR+HR	as needed	1	Night	response	10%
Screen Flats LSS, MOS, MXU	SR+HR	every 3d	5	Day	normalized flat	5%
Screen Arcs LSS, MOS, MXU	SR+HR	every 3d	1	Day	dispersion coeff.	0.3 pixel (3)
Flux std spectroscopic	SR	weekly (5)	1	Night	response	10%
Imaging Sky Flats without polarizers	SR	weekly	5	Twilight	normalized flat	2%
IPOL polarized std	SR	as needed	1	Night	zero angle (lin)	1 degree
IPOL unpolarized std	SR	annually	1	Night	instr. pol (lin)	
IPOL unpolarized std	SR	annually	1	Night	instr. pol (cir)	
PMOS arcs	SR	every 3d	1	Day	dispersion coeff.	0.3 pixel (3)
PMOS flats (0lin, 45circ)	SR	every 3d	5	Day	normalized flat	5%
PMOS polarized std	SR	as needed	1	Night	zero angle (lin)	1 degree
PMOS unpolarized std	SR	annually	1	Night	instr. pol (lin)	
PMOS unpolarized std	SR	annually	1	Night	instr. pol (cir)	
HIT-I Twilight Flats	SR	every 5d	5	Twilight	normalized flat	2%
HIT-I Screen Flats	SR	every 5d	5	Day	normalized flat	5%
HIT-S Screen Flats	SR	every 3d	5	Day	normalized flat	5%
HIT-S Screen Arcs	SR	every 3d	5	Day	dispersion coeff.	0.3 pixel (3)
HIT-MS Screen Flats	SR	every 3d	5	Day	normalized flat	5%
HIT-MS Screen Arcs	SR	3d	1	Day	dispersion coeff.	0.3 pixel (3)

Table 4.1: FORS Calibration Plan Tasks. "std" means standard star.
Notes: (1) only during FORS2 observing runs; (2) for (U)BVRI filters only and under photometric conditions only; (3) internal accuracy - not considering instrumental flexures - see Section 2.4.3; (4) Frequency as needed denotes that the calibration task is done if the subsequent mode was used; (5) Please note that the flux standard to calibrate LSS mode is taken with a MOS slit of 5" (at the position of the used slit) to include all the flux. The frequency of each calibration is based on the validity period of each calibration type.

FORS/UT	Coll.	Target	Filter	Scale (arcsec/pix)
FORS1/Antu	SR	47 Tuc	I	0.20013±0.00005
FORS1/Antu	HR	47 Tuc	I	0.09975±0.00004
FORS2/Yepun	SR	47 Tuc	I	0.12604±0.00003
FORS2/Yepun	SR	Pal 3	I	0.12607±0.00003
FORS2/Yepun	HR	Pal 3	I	0.06323±0.00003
FORS/UT (June 2004)	Coll.	Target	Filter	Scale (arcsec/pix)
FORS1/Kueyen	SR	ω Cen	I	0.20036±0.00008
FORS1/Kueyen	SR	ω Cen	I	0.20047±0.00007
FORS2/Antu	SR	ω Cen	I	0.12591±0.00002
FORS2/Antu	SR	ω Cen	I	0.12591±0.00002
FORS2/Antu	SR	ω Cen	I	0.12590±0.00003

Table 4.2: Image scales for the FORS instruments.

coordinate system. From the optics design it was estimated that the chromatic and thermal effects are of the order of 10% of the distortion.

The radial field distortion of FORS2 was measured with a pinhole MXU mask. The offsets are expressed in units of 24 micron pixels even though measured with 15 micron pixels of the new MIT detectors ($\Delta r'$ and r' in pixels measured on the MIT CCDs):

$$\text{FORS2 SR:} \quad \Delta r = 2.113{*}10^{-9}{*}r^3 - 2.158{*}10^{-6}{*}r^2 + 0.537{*}10^{-3}{*}r$$
$$\text{FORS2 HR:} \quad \Delta r = 7.133{*}10^{-9}{*}r^3 + 3.782{*}10^{-6}{*}r^2 + 0.160{*}10^{-3}{*}r$$

$$\text{with:} \quad r = r' * (15/24 * \text{binning})$$
$$\Delta r' = \Delta r/(15/24 * \text{binning})$$

The images scale was determined using astrometric standard stars in the star clusters 47Tuc and Pal 3 in several nights during commissioning of the instruments. The plate scales have also been measured in June 2004 when FORS2 was moved to Antu and FORS1 to Kueyen. In this case three fields of standard UCAC2 stars in the vicinity of the cluster ω Centauri have been used. The measured values are given in the table. For FORS2 the scale is given for unbinned 15 micron pixels in SR mode.

4.3 Data Reduction of Pre-Imaging Data for the Mask Preparation

Pre-imaging data delivery: Soon after the pre-imaging is successfully taken, the data are transferred to the ESO data archive in Garching, where it is available to the PI, through the User Portal.

Shift and add only: The mask preparation for FORS2 MOS, PMOS, and MXU modes will require that the original scale and field distortion is the same in reduced data as it was for the raw data. This is required since the FIMS tool will correct for the scale distortion in case of FORS pre-images at the time when the masks are saved. Advanced techniques to combine jitter images such as drizzle will require some distortion corrections before the techniques will be applied. It is strongly recommended only to use clean shift and add techniques (e.g., IRAF `imcombine`) to reduce images which are thought to be used for FIMS mask preparation.

FORS mosaics - don't cut the edges: In case of pre-imaging data taken with the FORS1 or 2 mosaic detectors, it will be required to keep the original file format of the pre-images. Vignetted parts of the images and pre- and overscan regions must not be cut before using the files with the FIMS software. The plug-in function `fsmosaic` delivered with the FIMS software can be used to merge the two files safely:

fsmosaic RAW_INPUT_FILE OUTPUT_FILE

The merged output files could be now combined with standard software such as `imcombine` (e.g., for IRAF imcombine: a median of the jittered files with the offset parameter set to wcs should give satisfactory results for the mask preparations). In general: first fsmosaic, and then imcombine!

The description of the functionality of the `fsmosaic` plug-in is given in the FIMS manual (see Section 1).

4.4 Flat-Fielding

4.4.1 Imaging Mode

Best results for flat fielding are obtained if the illumination is as similar as possible to that of the science frames. This can be achieved from four science frames with adequate S/N of the sky background taken with offsets $>5''$; fields should not be too crowded as well. This observing mode is supported by the corresponding templates. In order to achieve a suitable S/N of the resulting super-flatfield, a larger number of science frames may be needed if the sky level is low. If this is not guaranteed, twilight sky flats should be taken in addition. Night flats need to be carefully checked for remaining stars. Master night flats are processed by the reduction pipeline.

Calibration templates are also available to generate for any desired filter, sky flats during dusk or dawn, automatically determining the required exposure time from a brief windowed exposure, and taking into account the decreasing or increasing sky brightness in the evening or morning. Flat fielding from these exposures will, however, not remove large scale gradients (of the order of 1000 pixels). In service mode twilight flats are provided as standard calibration frames.

Screen flatfields can be taken (see Section 2.9) with the internal lamps and the screen in the telescope. A guide to approximate exposure times is given in Table 4.4. Screen flats should be used only for removing the high-frequency component of the flat field. However, this can be equally well achieved using sky flats, since the exposure levels in both are comparable. Furthermore, screen flats contain artificial reflections off the LADC (2–3 dots close to the image center) which need to be removed before using the flats. Screen flats are not provided as standard calibration frames in service mode, but need to be requested.

Table 4.3 lists results from the analysis of the flatfields (including master flats produced by the pipeline) taken during the past periods. The "sigma" values scale as sqrt(exposure level). All other values scale with the exposure level. The "sigma" in masters decreases by a factor $\sqrt{N}$ where N is the number of raw files used. The"diff_AB" is the fractional gain difference between the read-out ports A and B that is removed by the flattening. The "gradient" is the 'large'-scale gradient measured in a window of size 200x200 pixels.

Typical exposure level (ADU)	sigma noise, photon (raw)	sigma noise, fixed pattern	diff_AB	gradient (200×200 px)	
20000	0.6%	0.5%	18-25%	0.7%	

Table 4.3: Large-scale structure and small-scale noise in sky flats (high gain CCD readout)

Table 4.4 gives typical exposure times for screen flats for the SR collimator and Bessell filters. The numbers are indicative only since they are subject to changes due for instance to lamp replacements. The observatory staff has updated values at hand and takes also care of proper adjustments of the calibration exposure times for delivered service mode OBs (unless otherwise stated in the readme file of the program).

Lamp	U_SPECIAL	B	V	R	I	
exp. time (s)	200	4	4	6	10	

Table 4.4: Approximate exposure times (seconds) for FORS2 imaging screen flat calibrations for the Bessell and special broadband filters, SR collimator, high gain readout. The Blue+1 and Blue+2 lamps should be used.

4.4.2 Spectroscopic Modes

For the spectroscopic modes one will use internal screen flats in most cases. These flats are taken during daytime with the telescope pointing to zenith and the instrument in calibration position. Spectroscopic flats on the sky in twilight are not supported by the FORS standard templates.

A guide to exposure times is given in Table 4.5. In MOS mode some bleeding from zero order may occur for low dispersion grisms and unfavorable (i.e., wide spread in dispersion direction) object geometry. The numbers are indicative only since they are subject to changes due for instance lamp replacements. The observatory

staff has updated values at hand and takes also care of proper adjustments of the calibration exposure times for delivered service mode OBs (unless otherwise stated in the readme file).

Please note that red internal flat field lamps (FlatRed+1 and FlatRed+2) cannot be used anymore after the installation of the external calibration units (see Section 2.9).

Grism	OSF	Exposure time (s)	
		E2V	MIT
1400V	—		27.3
1200B	—	21.9	27.3
1200g	—	21.9	27.3
1200R	GG435		11.5
1028z	OG590		9.1
600B	—	11.8	8.3
600V	GG435	12.5	
600R	GG435	15.4	
600I	OG590	34.0	7.0
600RI	GG435		3.8
600z	OG590		5.2
300V	—/GG435	5.2	9.0
300I	—/OG590	9.8	4.0
200I	—		1.2
150I	—/OG590/GG435	2.3	1.1

Table 4.5: Approximate exposure times (seconds) for spectroscopic screen flat calibrations with the 2 available mosaics. Flatfield lamps of one calibration unit switched on. Approximate exposure level is 30000 ADU. Slit width = 1″, SR collimator, high gain readout, 2x2 binning. OSF = Order Separation Filter.

Grism	OSF	He	HgCd	2*Ar	2*Ne
1400V	—	100	25	0	100
1200B	—	100	100	0	0
1200R	GG435	75	0	37	7
1028z	OG590	100	0	5.5	100
600B	—	100	25	0	0
600V	GG435	50	50	10	10
600R	GG435	0	50	10	10
600RI	GG435	90	40	4.5	4.5
600z	OG590	75	0	4.5	75
300V	—/GG435	70	17.5	9.8	0
300I	OG590	100	0	5	0
200I	—	70	0	4.9	0
150I	—/OG590/GG435	60	18	6	0

Table 4.6: Approximate exposure times and switch-on times of calibration lamps (seconds) for wavelength calibrations with FORS2. Any slit width, SR collimator, high gain readout, 2x2 binning. The update with the integration times for the E2V mosaic is still pending.

4.5 Wavelength Calibration

For the wavelength calibration one may use the He, HgCd, and Ar lamps (at the lowest spectral resolution — grism 150I) and in addition the Ne lamp (at higher resolution). Note that the switch-on times can be defined individually for each lamp in the corresponding calibration template. For grism 600B the HgCd lamp must be used. Approximate exposure times for well exposed spectra are given in Table 4.6 for the different grisms and lamps, for a slit width of 1″. Calibration spectra taken with the different grisms are plotted in figures D–D.

The given numbers are indicative only since they are subject to changes due to, e.g., lamp replacements. The observatory staff has updated values at hand and takes also care of proper adjustments of the calibration

exposure times for delivered service mode OBs (unless otherwise stated in the README file).

Wavelength calibration exposures are done during the day only with the telescope in zenith and the instrument in calibration position.

4.6 Calibrating Polarimetric Measurements

4.6.1 Circular polarimetry

The amount of circular polarization V can be determined by observing with the quarter wave retarder plate at two retarder plate angles of $\theta = \pm 45°$, by the equation:

$$V = \frac{1}{2}\left[\left(\frac{f^o - f^e}{f^o + f^e}\right)_{\theta=45} - \left(\frac{f^o - f^e}{f^o + f^e}\right)_{\theta=-45}\right] \tag{4.1}$$

(f^o, f^e being the ordinary and extraordinary beam of the object measured for a given retarder plate angle θ)

One could determine the circular polarization observing at one retarder plate position, but two observations are required to eliminate the strongest observing biases in the first order approximation:

- the improper flat field correction ϵ_{FF}
- the colour dependent offset ϵ_θ to the nominal retarder plate zero angle
- the incomplete and colour dependent retardation of $90 + \epsilon_\Phi(\lambda)$ degree of the quarter wave plate

Observations at only one retarder plate angle would cause hardly correctable Stokes parameter cross talks in the case of objects with non-negligible linear polarization. The colour dependence of the retarder angle ϵ_θ would cause an additional polarization of $\Delta V = -2\epsilon_\theta U$ and the incomplete retardation ϵ_Φ ($\Phi \neq 90$ degree, quarter wave) would cause the additional polarization of $\Delta V = -\epsilon_\Phi Q$ (ϵ_Φ & ϵ_θ in radians, UVQ being the Stokes parameters). One would get

$$\left(\frac{f^o - f^e}{f^o + f^e}\right)_{\theta=45} = V + \epsilon_{FF} + (-2\epsilon_\theta U - \epsilon_\Phi Q) \tag{4.2}$$

$$\left(\frac{f^o - f^e}{f^o + f^e}\right)_{\theta=-45} = -V + \epsilon_{FF} + (-2\epsilon_\theta U - \epsilon_\Phi Q) \tag{4.3}$$

The difference between the two observations yields V while the small deviations have the same sign in the two equations and are therefore eliminated for small angles ϵ_Φ & ϵ_θ.

4.6.2 Linear Polarimetry

After the pre-reduction of the spectroscopic data and integration of the ordinary and extraordinary target spectra or flux $f^o(\theta_i)$ and $f^e(\theta_i)$, the normalized flux differences $F(\theta_i)$ must be calculated:

$$F(\theta_i) = \frac{f^o(\theta_i) - f^e(\theta_i)}{f^o(\theta_i) + f^e(\theta_i)}, \tag{4.4}$$

where $\theta_i = i * 22.5°$ is the angle of the retarder plate ($0 < i < 15$).

If the polarimetry is obtained from the normalized flux differences, no absolute flux calibration of the data is required. In this case, the Stokes parameters Q and U can be derived via Fourier transformation:

$$Q = \sum_{i=0}^{N-1} \frac{2}{N} F(\theta_i)\cos(4\theta_i) \tag{4.5}$$

$$U = \sum_{i=0}^{N-1} \frac{2}{N} F(\theta_i)\sin(4\theta_i) \tag{4.6}$$

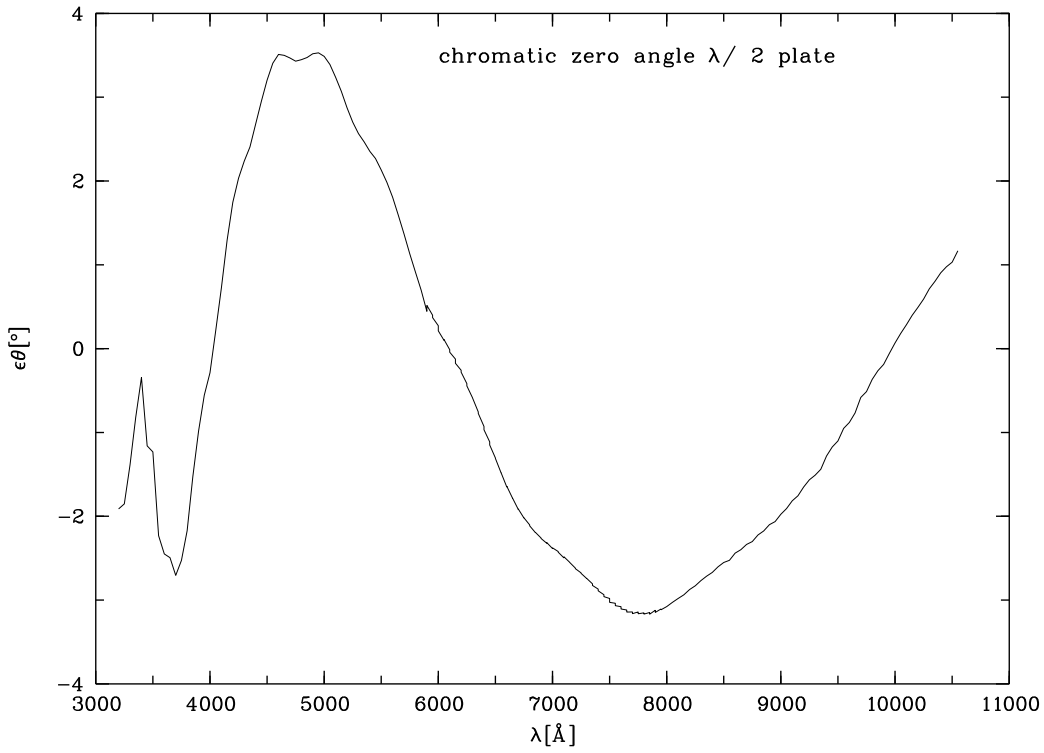


Figure 4.1: Chromatism of the half wave plate

In principle, two observations at different retarder angles ($N = 2$) are sufficient to calculate Q and U. At least four measurements at angle 0.0 to 67.5 are needed to suppress the impact of the improper flat fielding of the data. Best results will be obtained, if observations at all the rotation angles of the retarder plate ($N = 16$) will be carried out.

Although a super-achromatic half wave plate is used with FORS2, the zero angle of the plate is not negligible. Therefore, all raw measurements of polarization position angles are rotated by an angle of a few degrees. For the half wave plate the chromatic dependence of the zero angle was determined with an aligned Glan-Thomson prism. The tabulated values of the zero angle as displayed in figure 4.1 can be obtained on request.

For imaging polarimetry the offset angles can be determined by convolving the filter response curves with the colour dependence of the half wave plate. The results are given in Table 4.7. Measuring a polarization angle of, e.g., $\theta = 134.20$ deg in the Bessel B filter one would correct this raw measurement to a final result of $\theta = 132.66$ deg. The offset angles should be confirmed periodically by the observation of polarized standard stars.

4.7 Pipeline Reduction

A data reduction pipeline is operational for FORS2, except for imaging polarimetry (IPOL) and high time resolution observations (HIT, HIT-S, HIT-MS). The FORS2 pipeline is implemented in gasgano, esorex and reflex and a Cookbook is available on the FORS2 web page.

4.7.1 Supported modes

The FORS pipeline supports four instrumental modes: imaging (IMG), longslit spectroscopy (LSS), multi-object spectroscopy (MOS/MXU), and spectro-polarimetry (PMOS). It provides :

- creation of master calibration products

zero angles – imaging mode	
Filter	ϵ_θ
Bessel U	-2.07deg
Bessel B	+1.54deg
Bessel V	+1.80deg
Bessel R	-1.19deg
Bessel I	-2.89deg
Gunn u	-2.03deg
Gunn v	-0.47deg
Gunn g	+3.10deg
Gunn r	-1.31deg
Gunn z	-1.64deg

Table 4.7: Calibration of the FORS half wave retarder plate in imaging mode from the spectroscopic measurements with the Glan-Thompson prism. These values will depend slightly on the colour of the observed targets.

- photometric zero points and spectral response
- reduction of science data, incl. flux-calibration of spectroscopic data

For IMG data, the raw data are bias subtracted and flat fielded and SExtractor is used to detect and classify sources. The single frames taken within a sequence are not combined.
LSS, MOS, and MXU data, in addition to de-biasing and flat fielding (high spatial frequencies only), are rebinned to wavelength space. The spatial curvature is corrected for MOS and MXU data and also for LSS, provided the appropriate GLOBALDISTORTION_TABLE exists for the given combination of grism and filter. Spectrophotometric standard star observations are reduced like LSS science data, and a response curve is determined. The night sky is subtracted, usually on the non-rectified frame. A median sky subtraction working on the rectified frame is available as well. This will also not work properly if more than 50% of the pixels along the slit at a given wavelength contain signal from sources. This can cause problems for extended objects and crowded regions or for very short slits in the case of MXU. The sources are extracted, but the single frames taken within a sequence are not combined.

For LSS/MOS/MXU data a Reflex workflow exists which takes care of the classification and organisation of the input data and offers interactive windows to verify the quality of the results (and change parameters if necessary).

More information about the spectroscopic FORS pipeline can be found at

http://www.eso.org/observing/dfo/quality/FORS1/pipeline/fors_calib.html

(calibration data) and

http://www.eso.org/observing/dfo/quality/FORS1/pipeline/fors_science.html

(science data). The pipeline can be downloaded from

http://www.eso.org/sci/software/pipelines/

4.7.2 Quality Control Pipeline

All pipeline supported calibration data are reduced by the quality control group in Garching.

All raw calibration data from the pipeline-supported modes of FORS (regardless of whether they are obtained for science data in visitor or in service mode) are processed to obtain master calibration data, which are quality-checked and provide information on the instrument health (see http://www.eso.org/observing/dfo/quality/FORS2/reports/HEALTH/trend_report_BIAS_med_master_HC.html and links on that page). The fact that a fixed set of parameters has to be used for the automatic processing may cause problems in a few cases, for instance if MOS/MXU data have slitlets at very large offsets.

Master calibration data are of the following types:

- MASTER_BIAS (bias level, read-out noise),
- MASTER_SKY_FLAT_IMG (high and low spatial frequency flat, taken in twilight),
- photometric zero points (from standard star observations),
- MASTER_NORM_FLAT_LSS (high spatial frequency flat, slit function),
- DISP_COEFF_LSS (wavelength calibration).
- WAVELENGTH_MAP_LSS (image in which each pixel has its wavelength as pixel value)
- MASTER_NORM_FLAT_MOS/MXU (high spatial frequency flat),
- SLIT_LOCATION_MOS/MXU (table with the slit positions and edges)
- DISP_COEFF_MOS/MXU (dispersion coefficients from the wavelength calibration).
- CURV_COEFF_MOS/MXU (coefficients to describe and correct the spatial curvature of the spectra)
- WAVELENGTH_MAP_MOS/MXU (image in which each pixel has its wavelength as pixel value)
- SPATIAL_MAP_MOS/MXU (image in which each pixel has its position along the slit as pixel value)

Usually MASTER_SKY_FLAT_IMG are used for flat-fielding IMG data. This removes all multiplicative artifacts in the image (pixel-to-pixel gain variations, instrument, and CCD efficiency). Since the illumination during dusk/dawn is, however, different from night conditions, a large-scale gradient of a few percent may remain which can be easily removed by, e.g., fitting a polynomial. For limits on the FORS2 photometric accuracy see Moehler et al. (2010, PASP 122, 93) and Coccato et al. (2014, MNRAS 438, 1256).

A better large-scale illumination correction can in some cases be obtained from night flats which are processed from jittered science images, which is not part of the QC processing.

Photometric zero points are routinely calculated for the standard Bessell or special broadband filters of the instrument. They are derived from the flux of the stars in e^-, not in ADU. They are meant for monitoring purposes and should **not be used for scientific data without careful checks** (see http://www.eso.org/observing/dfo/quality/FORS2/qc/zeropoints/zeropoints.html#frame). In particular, they use default values for extinction and colour coefficients that may not be appropriate for a given night. More refined processing is performed with about 4 weeks delay, when the zeropoints and nightly extinction coefficients are determined from a larger data set observed during photometric nights. For details see http://www.eso.org/observing/dfo/quality/FORS2/qc/zeropoints/zeropoints.html#stable and http://www.eso.org/observing/dfo/quality/FORS2/qc/zeropoints/zeropoints.html#night

4.7.3 Paranal Science Operation Pipeline — IMG, LSS and MOS/MXU modes only

In parallel to Garching, the FORS2 pipeline is in operation on Paranal. This allows the staff and visiting astronomer to better estimate the quality of the data. **The on-site pipeline is operated with "frozen" calibration data, updated only occasionally, and therefore are not the most recent ones.** Note also that the calibration database can be incomplete (in particular in longslit mode) due to the high number of longslits, grisms and filters combinations, and therefore only a part of the data will be processed. Therefore a special recipe was developed for the spectroscopic data, which allows one to get quick-look results without dedicated calibrations.

The Paranal pipeline works on a dedicated machine. Reduced science data are computed shortly after they have been exposed and are transmitted for inspection to the off-line user workstation.

The on-site pipeline will deliver the following products:

- master bias frames
- master twilight flats (IMG mode)

- flat fielded science images (IMG mode)
- photometric zero points (IMG mode)
- normalized master screen flats (LSS, MOS, MXU mode)
- wavelength calibration products (LSS, MOS, MXU mode)
- reduced science data (quick-look only) (LSS, MOS, MXU mode)

Appendix A

Abbreviations and Acronyms

The following abbreviations and acronyms are used in this manual:

ACQ	Acquisition
ADU	Analogue-to-Digital Unite
BOB	Broker of Observation Blocks
CCD	Charge Coupled Device
DDTC	Director's Discretionary Time Committee
DSS	Digital Sky Survey
ECH	Echelle Spectroscopy
ESO	European Southern Observatory
ETC	Exposure Time Calculator
FIERA	Fast Imager Electronic Readout Assembly
FIMS	FORS Instrumental Mask Simulator
FITS	Flexible Image Transport System
FORS	Focal Reducer/Low Dispersion Spectrograph
FWHM	Full Width Half Maximum
HIT	HIgh-Time resolution
HR	High Resolution
IDL	Interactive Data Language
IMG	Imaging
IPOL	Imaging Polarimetry
IRAF	Image Reduction and Analysis Facility
ISF	Instrument Summary File
LADC	Longitudinal Atmospheric Dispersion Compensator
LSS	Long Slit Spectroscopy
MIDAS	Munich Image Data Analysis System
MOS	Multi Object Spectroscopy
MXU	Mask eXchange Unit
OB	Observation Block
OSF	Order Separation Filter
OT	Observing Tool
PMOS	Polarimetric Multi Object Spectroscopy
PSF	Point Spread Function
P2PP	Phase 2 Proposal Preparation
RMS	Root Mean Square
RON	Read Out Noise
RQE	Responsive Quantum Efficiency
SR	Standard Resolution
S/N	Signal-to-Noise
TBC	To Be Confirmed
TBD	To Be Defined
TCS	Telescope Control System

UV	Ultraviolet
VIMOS	Visible Multi-Object Spectrograph
VLT	Very Large Telescope
WCS	World Coordinate System

Å	Ångström
e^-	Electron
cm	Centimeter
h	Hour
kpx	KiloPixel
min	Minute
mm	Millimeter
nm	Nanometer
px	Pixel
s	Second
μm	Micrometer

Appendix B

FORS Filter Characteristics

B.1 Broadband Filters

Table B.1 lists all currently (see issue date of this document) available FORS2 broadband filters. The transmission curves are given thereafter. Tables of the measured transmission values are available via the ESO web pages:

http://www.eso.org/sci/facilities/paranal/instruments/fors/inst/Filters/curves.html
http://filters.ls.eso.org/efs/index.htm

Filter	λ_0 (nm)	FWHM (nm)
U_HIGH+112	361	50.5
B_HIGH+113	437	102.0
V_HIGH+114	555	123.2
g_HIGH+115	467	160.3
R_SPECIAL+76	655	165.0
I_BESS+37/+77	768	138.0
Z_SPECIAL+43	916	18.4
U_BESS+33 (3)	366	36.0
U_SPECIAL+73 (3)	362	29.0
B_BESS+34/+74 (3)	429	88.0
V_BESS+35/+75 (3)	554	111.5
R_BESS+36 (3)	657	150.0
u_GUNN+38 (3)	359	33.5
v_GUNN+39(3)	398	46.0
g_GUNN+40 (1) (3)	506	79.5
r_GUNN+41(3)	653	81.5
z_GUNN+78	910	130.5
GG435+81 (2)	edge filter: n/a	n/a
OG590+32 (2)	edge filter: n/a	n/a
FILT_465_250+82 (2) (3)	465	250

Table B.1: Characteristics of the FORS2 broadband filters. λ_0 is the central wavelength in nm.
(1) this is located in one of the interference filter wheels, as it is physically designed as an interference filter
(2) these are intended as order separation filters for spectroscopy
(3) not available after P86

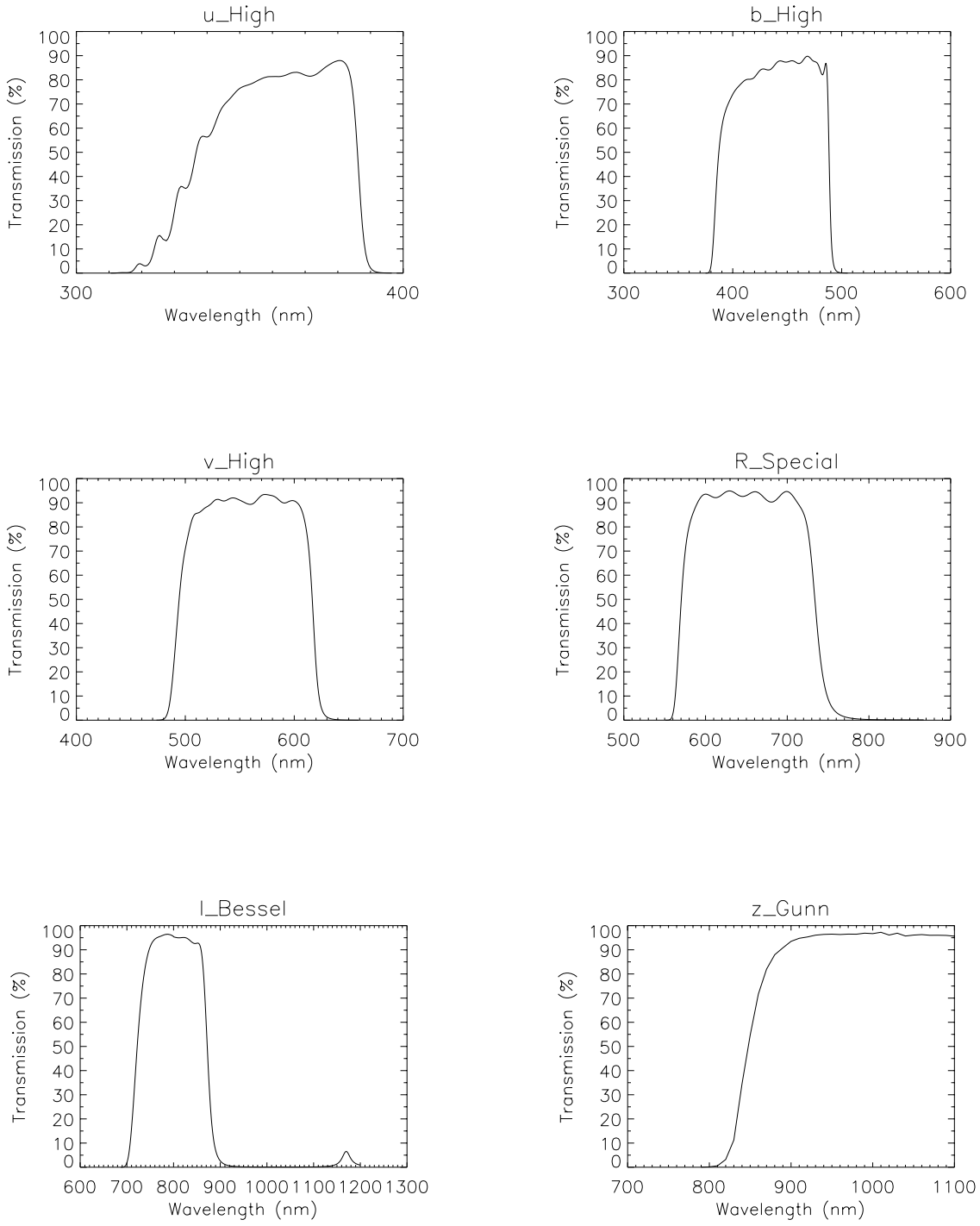


Figure B.1: Filter transmission curves for the standard instrument broadband filters.

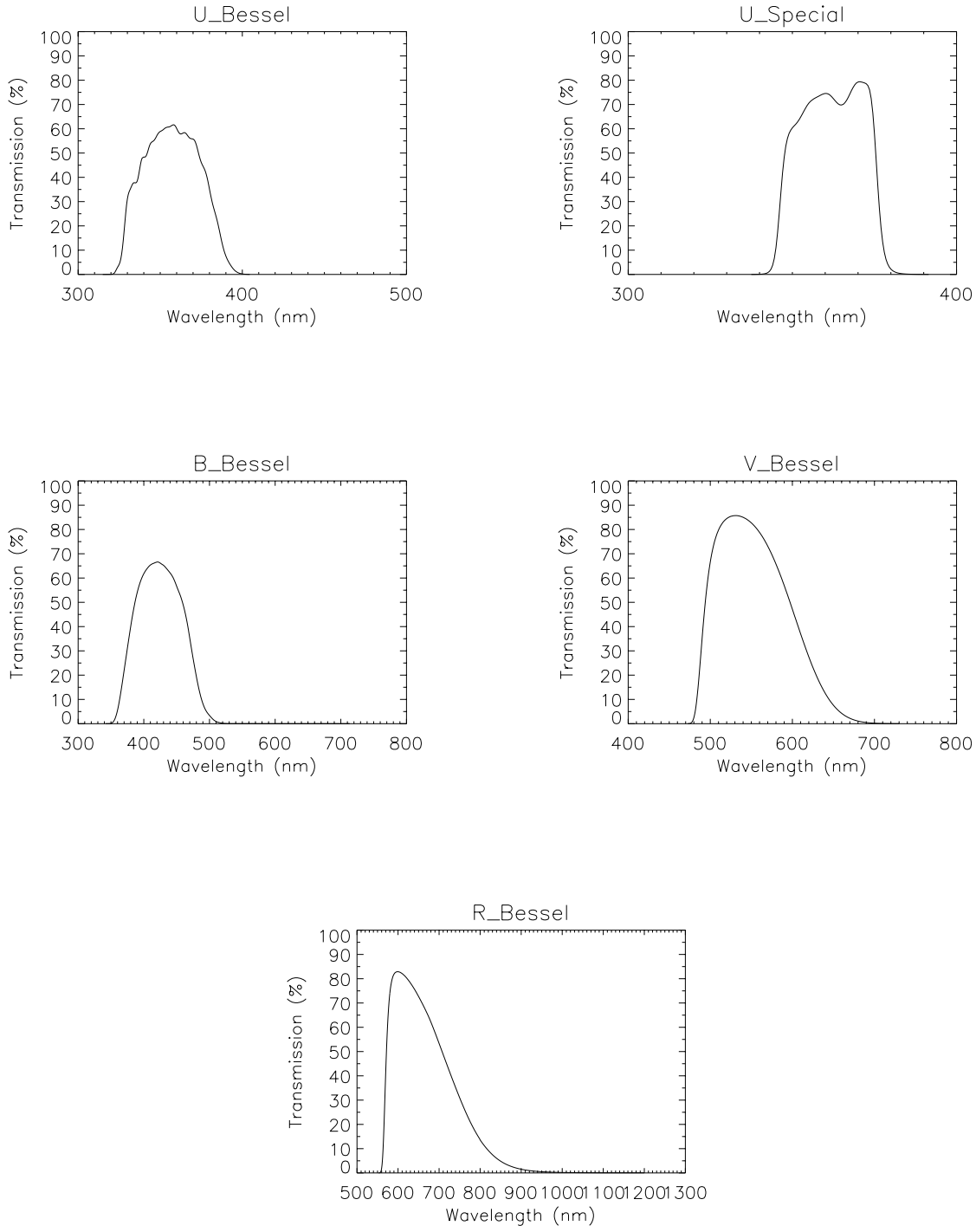


Figure B.2: Additional Bessell filter transmission curves.

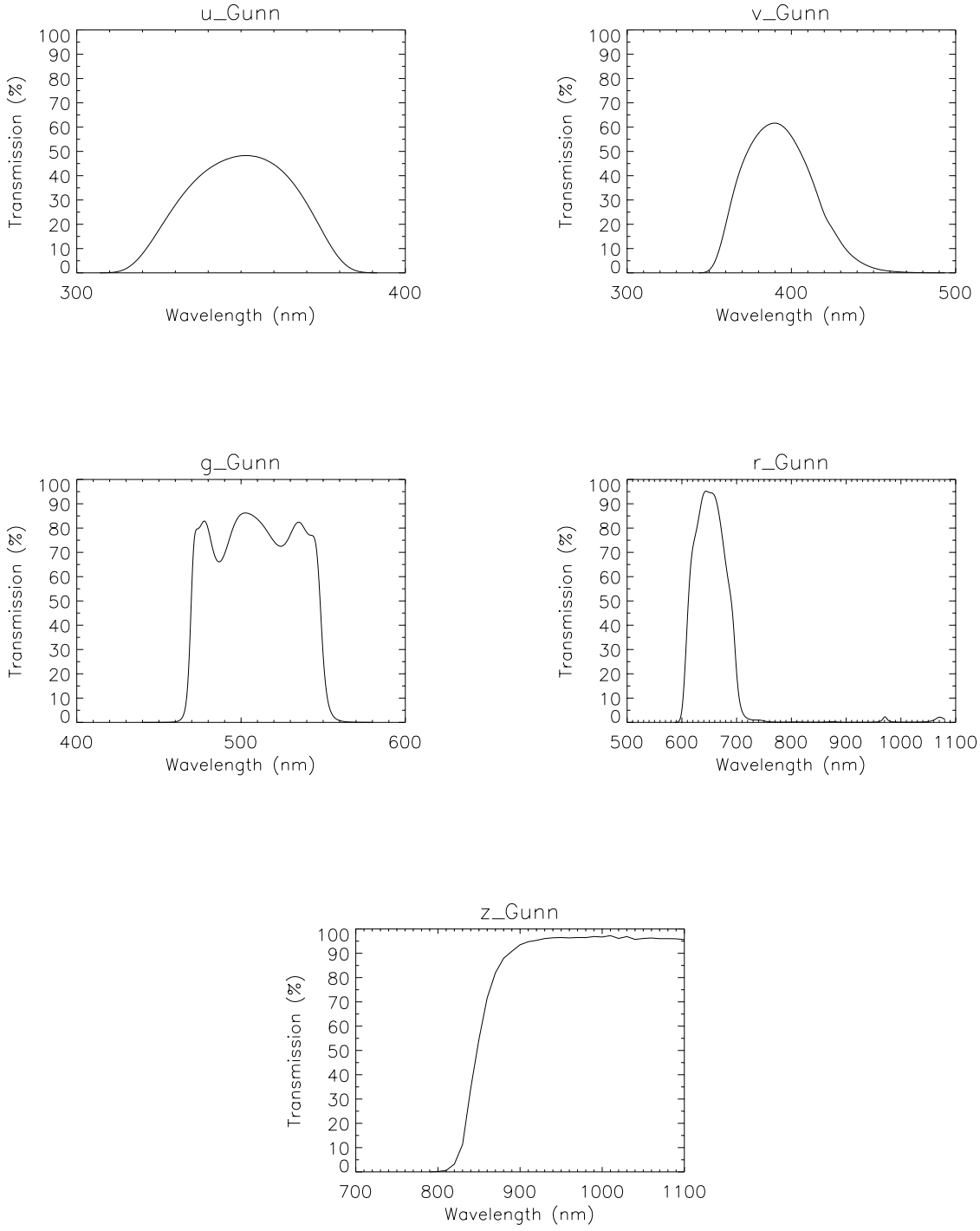


Figure B.3: Gunn filter transmission curves.

B.2 Interference Filters

Table B.2 lists all currently available FORS2 interference filters. Their characteristics are given with the FORS SR and HR collimators: central wavelength, peak transmission, and FWHM. Due to their location in the converging beam, the filter characteristics depend on the collimator used. The filter bandwidths are wider, the central wavelength is blue-shifted, and the peak transmission is lower than in a parallel beam. With the SR collimator, the effect is larger than with the HR collimator. The filters are centered on important emission lines and on 5% and 10% longer wavelengths.

		λ_0		T_0		FWHM (nm)		
Filter	Line	SR	HR	SR	HR	SR	HR	λ_0 shift
OII+44	[OII] 372.7	371.7	372.9	0.45	0.48	7.3	6.9	0%
OII/4000+45		377.6	378.8	0.37	0.40	6.5	6.1	5%
OII/8000+46		381.4	382.6	0.43	0.47	6.5	6.1	10%
HeII+47	HeII 468.6	468.4	469.1	0.79	0.82	6.6	6.4	0%
HeII/3000+48		472.6	473.4	0.76	0.79	5.8	5.6	5%
HeII/6500+49		478.1	478.9	0.78	0.81	6.8	6.6	10%
OIII+50	[OIII] 500.7	500.1	500.9	0.76	0.80	5.7	5.5	0%
OIII/3000+51		504.5	505.3	0.76	0.80	5.9	5.7	5%
OIII/6000+52		510.5	511.3	0.74	0.78	6.1	5.9	10%
HeI+53	HeI 587.6	586.6	587.6	0.79	0.84	6.0	5.7	0%
HeI/2500+54		592.0	593.0	0.77	0.81	6.8	6.5	5%
HeI/5000+55		597.5	598.5	0.85	0.89	7.4	7.2	10%
OI+56	[OI] 630.0	629.5	630.6	0.75	0.79	7.2	6.9	0%
OI/2500+57		635.4	636.4	0.75	0.81	5.9	5.5	5%
OI/4500+58		640.4	641.4	0.77	0.83	6.3	6.0	10%
H_Alpha+83	Hα 656.3	656.3	657.4	0.70	0.76	6.1	5.7	0%
H_Alpha/2500+60		660.4	661.5	0.77	0.83	6.4	6.1	5%
H_Alpha/4500+61		666.5	667.6	0.72	0.77	6.5	6.1	10%
SII+62	[SII] 672.4	672.8	673.9	0.77	0.82	6.6	6.3	0%
SII/2000+63		677.4	678.5	0.77	0.82	6.8	6.5	5%
SII/4500+64		683.2	684.3	0.72	0.78	6.4	6.0	10%
SIII+65	[SIII] 953.2	952.3	953.9	0.68	0.80	5.9	5.2	0%
SIII/1500+66		957.2	958.8	0.72	0.84	6.3	5.6	5%
SIII/3000+67		962.1	963.7	0.70	0.83	5.9	5.2	10%
FILT_388_4		388		0.87		4		
FILT_485_37		485		0.89		37		
FILT_691_55		691		0.93		55		
FILT_815_13		815		0.90		13		
FILT_834_48		834		0.90		48		
z_SPECIAL		915		0.94		20		
FILT_917_6		917		0.85		6		
FILT_500_5	[OIII] 500.7	500		0.81		5		
FILT_503_5		503		0.83		5		
FILT_530_25		530		0.85		25		

Table B.2: Characteristics of the FORS interference filters. λ_0 is the central wavelength in nm, T_0 the peak transmission.

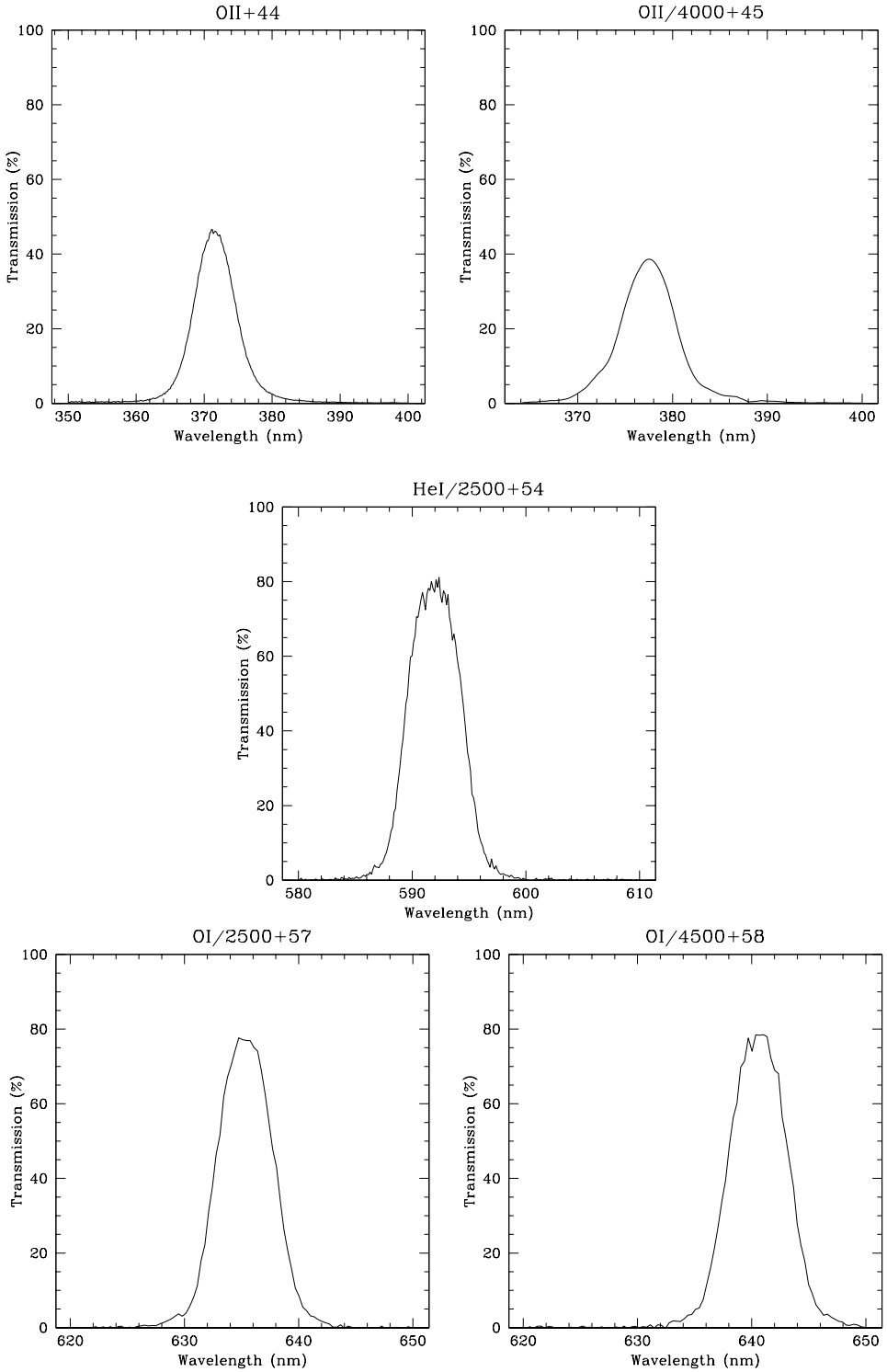


Figure B.4: FORS intermediate band filter transmission curves.

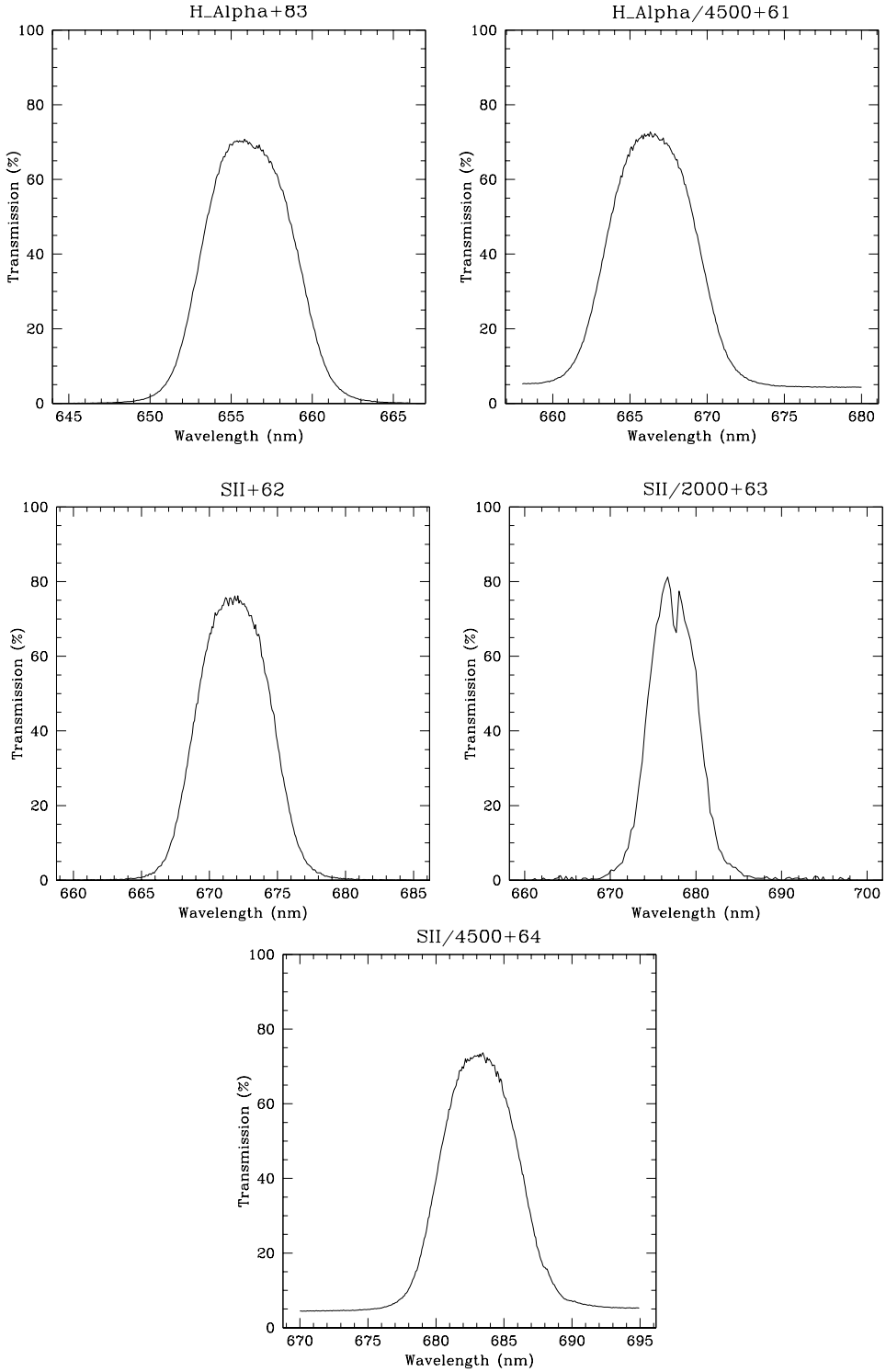


Figure B.5: FORS intermediate band filter transmission curves.

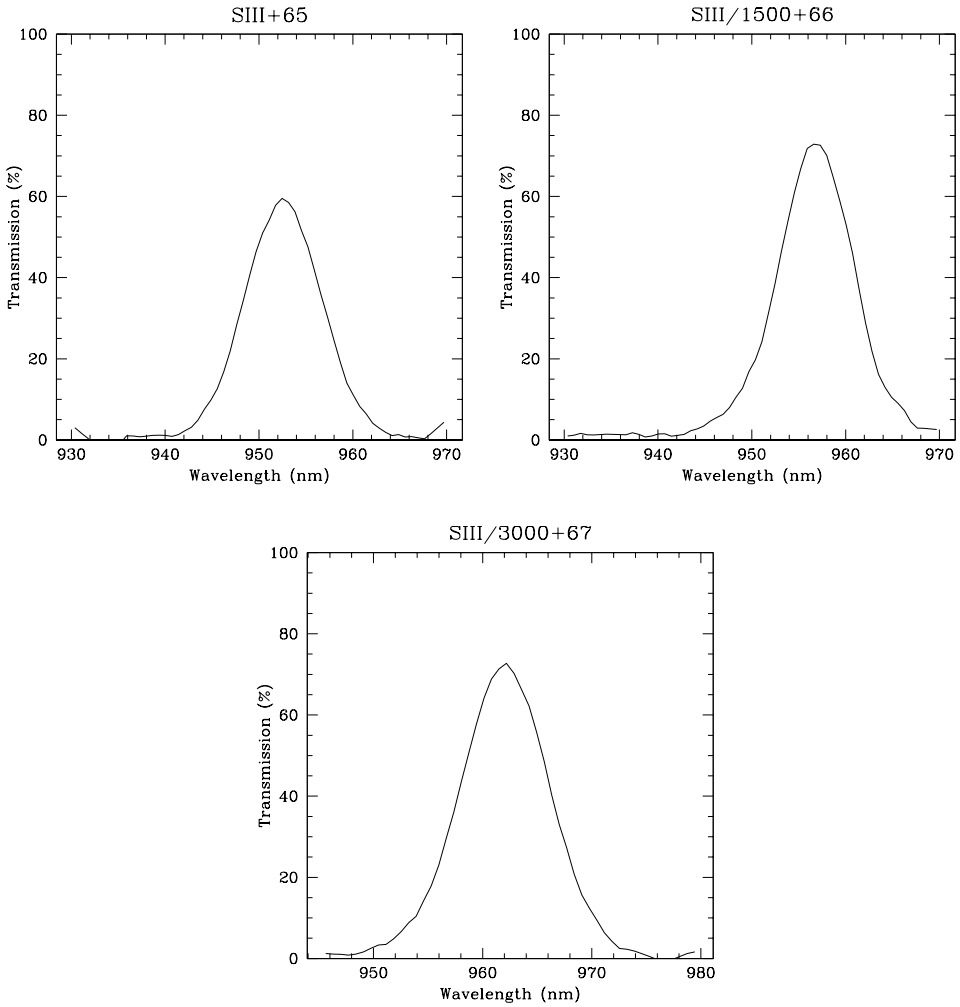


Figure B.6: FORS intermediate band filter transmission curves.

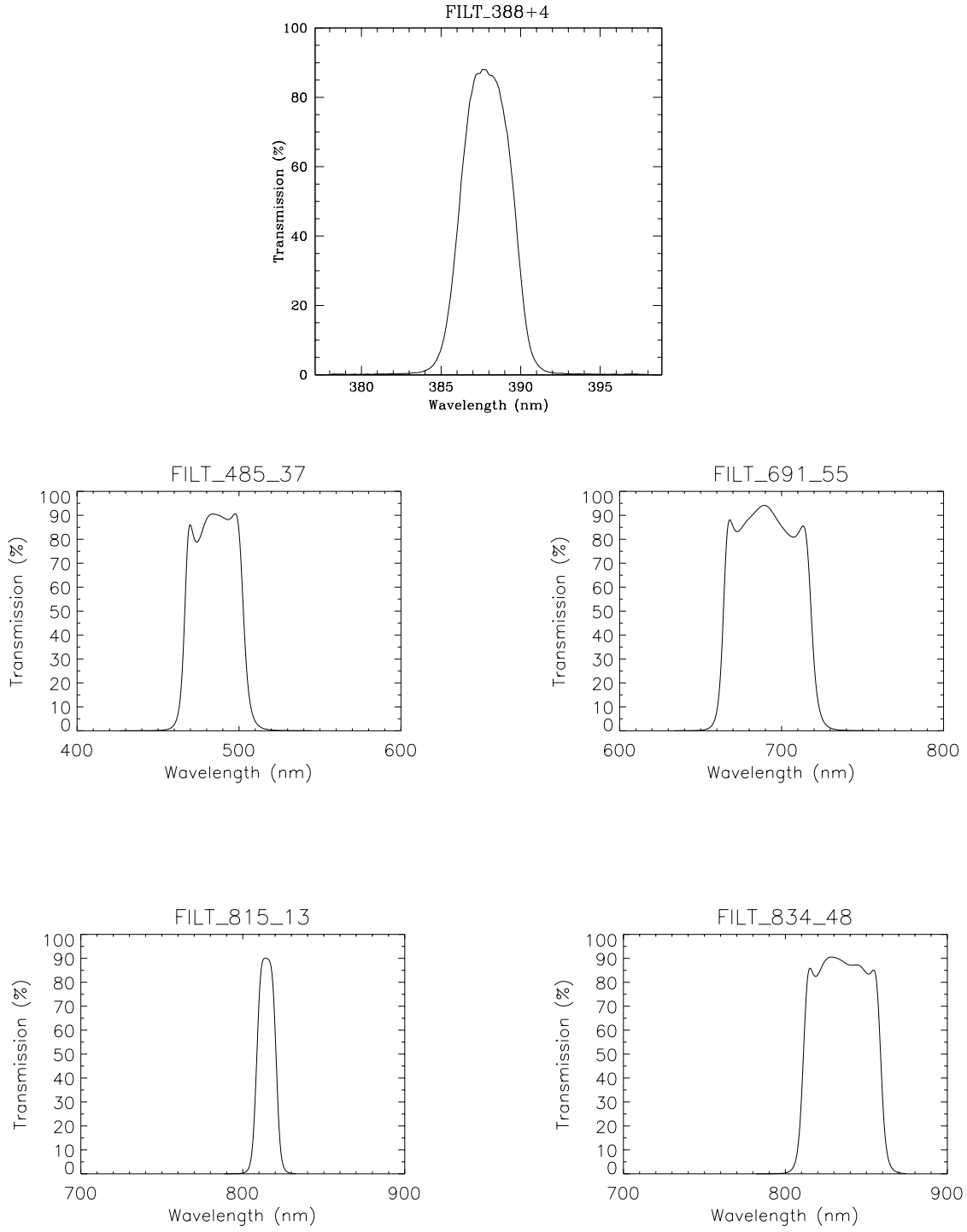


Figure B.7: FORS intermediate band filter transmission curves.

Appendix C

Efficiency Curves for the FORS Grisms

C.1 FORS2 Grisms

This appendix contains the efficiency curves of all standard grisms available for FORS2 and the approximate wavelength range for a slit which is located in the field centre. Tables of the measured efficiency values are available on the WEB page:

http://www.eso.org/sci/facilities/paranal/instruments/fors/inst/grisms.html

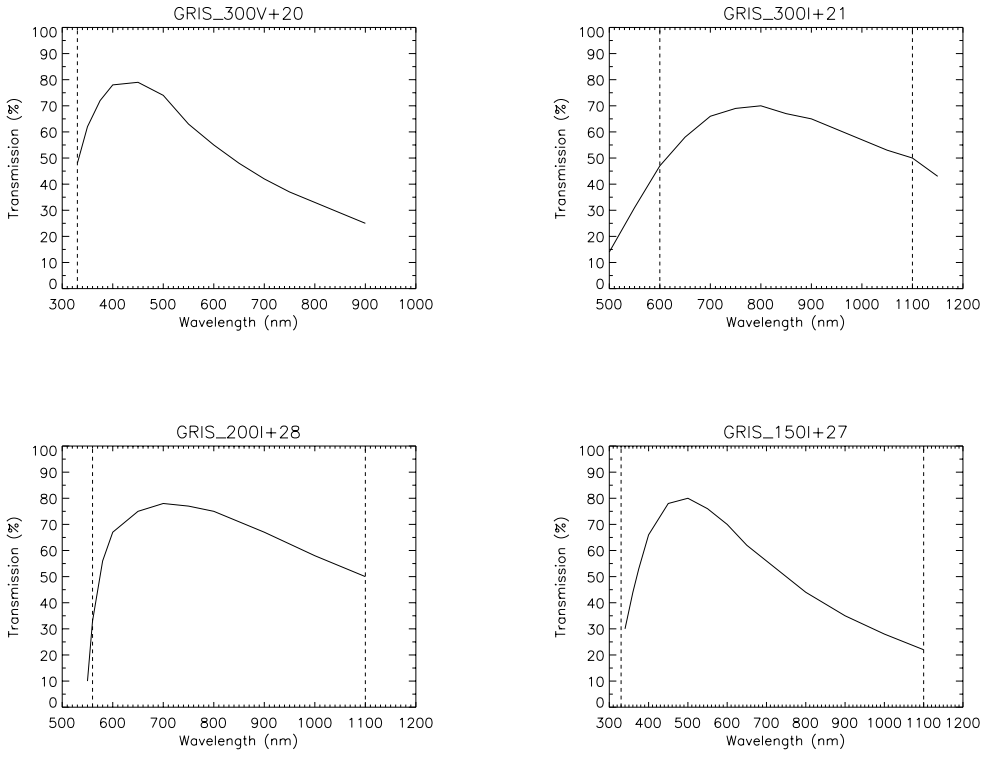


Figure C.1: Efficiency curves of the low resolution grisms. The vertical lines mark the approximate limits of the spectral range with the slit in the center of the field. The cutoff wavelength is in most cases given by the order separation filters, the red CCD limit or the 330nm limit of the FORS optics in the blue.

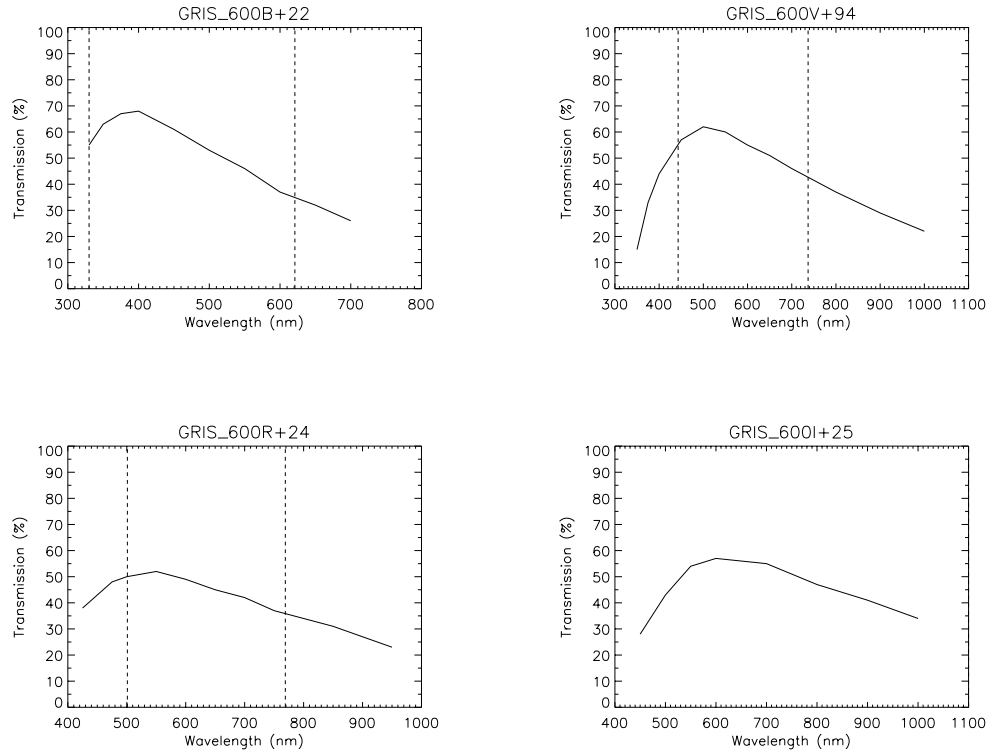


Figure C.2: Efficiency curves of the medium resolution grisms. The vertical lines mark the approximate limits of the spectral range with the slit in the center of the field.

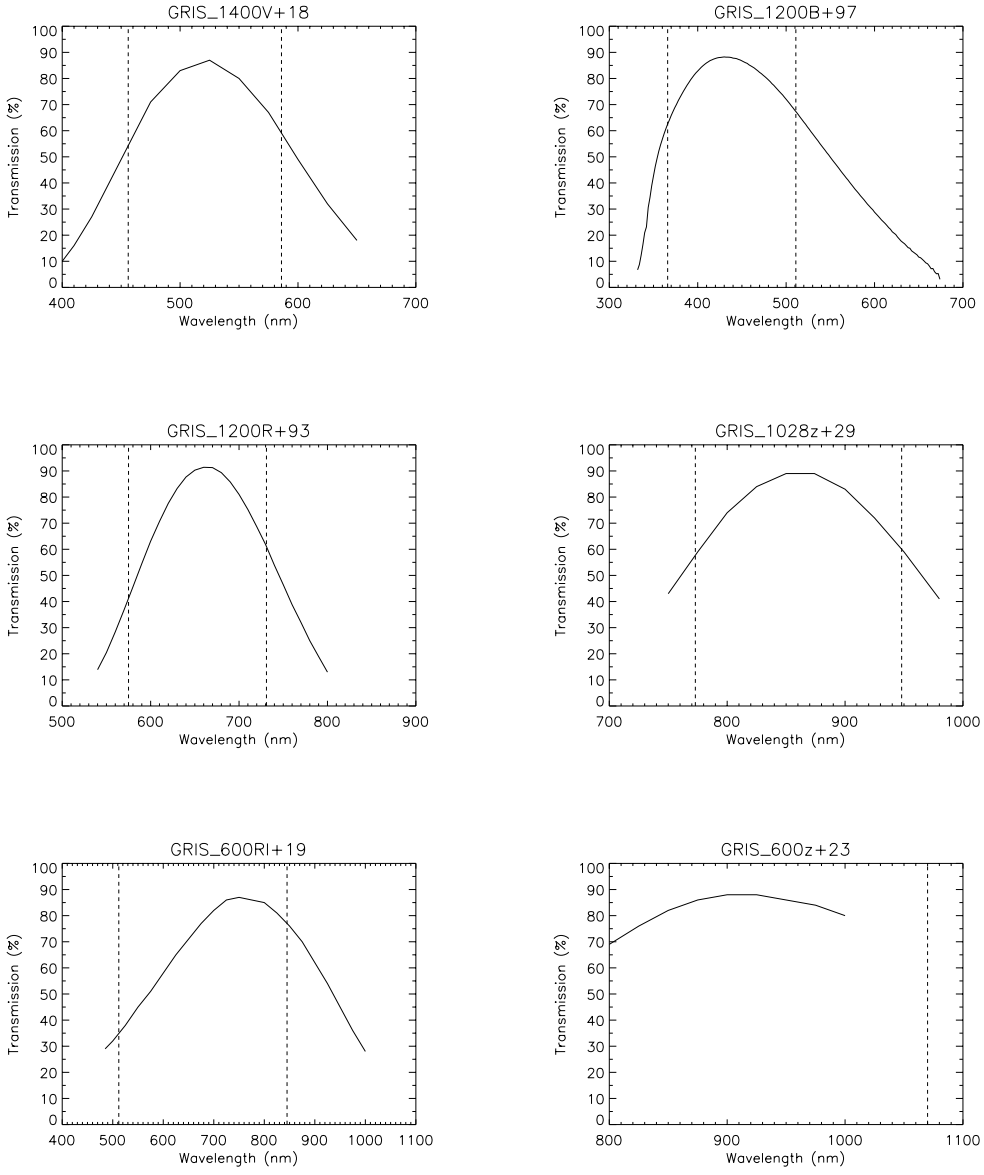


Figure C.3: Efficiency curves of the medium resolution volume phased holographic grisms. The vertical lines mark the approximate limits of the spectral range with the slit in the center of the field.

Appendix D

Wavelength Calibration Spectra for the FORS Standard Grisms

This appendix gives a wavelength table for the calibration lamps used in FORS2 together with the arc line spectra taken with the FORS grisms and the SR collimator. The measurements were done with MOS slits located in the center of the field of view and a slit width of 1.0 arcseconds.

Note: These plots are indicative only, since minor shifts of the wavelength pixels may occur between the two FORS instruments and due to different dewar mounting after instrument and CCD maintenance. The x-scale is in units of 2×2 binned pixels.

Wavelength (Å)	Element	Wavelength (Å)	Element
3610.500	Cd	7065.200	He I
3650.144	Hg	7081.880	Hg
3654.840	Hg	7091.990	Hg
3663.274	Hg	7147.041	Ar I
3888.646	He I	7173.939	Ne I
3964.700	He I	7245.167	Ne I
4026.200	He I	7272.930	Ar I
4046.557	Hg	7281.349	He I
4077.831	Hg	7346.200	Cd
4347.500	Hg I	7383.900	Cd
4358.343	Hg	7383.981	Ar I
4471.479	He I	7385.300	Cd
4678.160	Cd	7438.900	Ne I
4713.200	He I	7488.870	Ne I
4799.920	Cd	7503.868	Ar I
4916.070	Hg	7514.652	Ar I
4921.929	He I	7535.800	Ne I
5015.675	He I	7635.106	Ar I
5085.824	Cd	7724.210	Ar I
5341.100	Ne I	7948.176	Ar I
5400.562	Ne I	8006.157	Ar I
5460.742	Hg	8014.786	Ar I
5764.419	Ne I	8103.693	Ar I
5769.598	Hg	8115.311	Ar I
5790.656	Hg	8264.523	Ar I
5852.488	Ne I	8300.326	Ne I
5875.620	He I	8377.367	Ne I
5881.900	Ne I	8408.210	Ar I
5944.830	Ne I	8424.648	Ar I
5975.534	Ne I	8495.360	Ne I
6029.977	Ne I	8521.442	Ar I
6074.338	Ne I	8591.259	Ne I
6096.160	Ne I	8634.648	Ne I
6143.063	Ne I	8654.384	Ne I
6163.594	Ne I	8667.944	Ar I
6217.281	Ne I	8681.900	Ne I
6266.495	Ne I	8704.150	Ne I
6304.790	Ne I	8853.867	Ne I
6334.428	Ne I	8919.500	Ne I
6382.991	Ne I	9122.968	Ar I
6402.246	Ne I	9201.800	Ne I
6438.470	Cd	9224.499	Ar I
6506.528	Ne I	9300.850	Ne I
6532.880	Ne I	9354.218	Ar I
6598.953	Ne I	9425.380	Ne I
6678.149	He I	9657.784	Ar I
6678.300	Ne I	9784.501	Ar I
6717.040	Ne I	10140.000	Hg
6907.160	Hg	10394.600	Cd
6929.468	Ne I	10830.171	He I
6965.431	Ar I		
7032.413	Ne I		

Table D.1: Wavelengths of the arc lamp lines, with the corresponding element

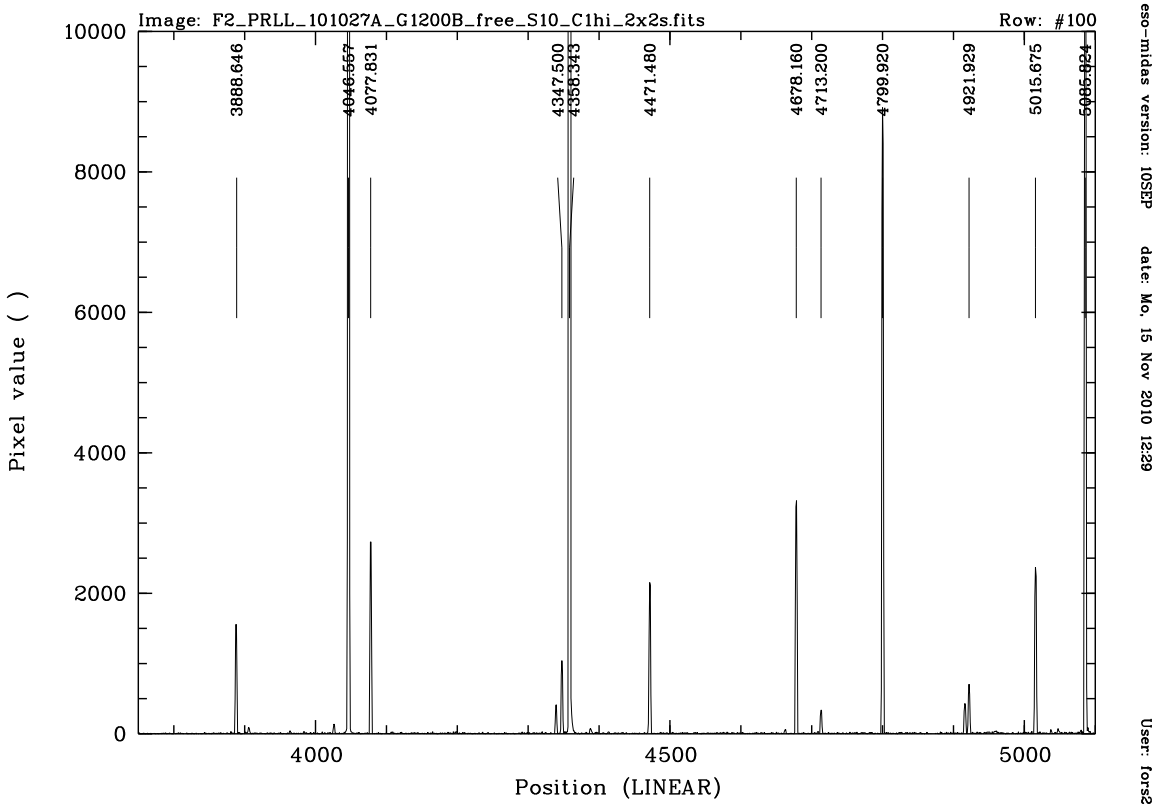


Figure D.1: Calibration spectrum taken with the SR collimator and grism GRIS_1200B+97

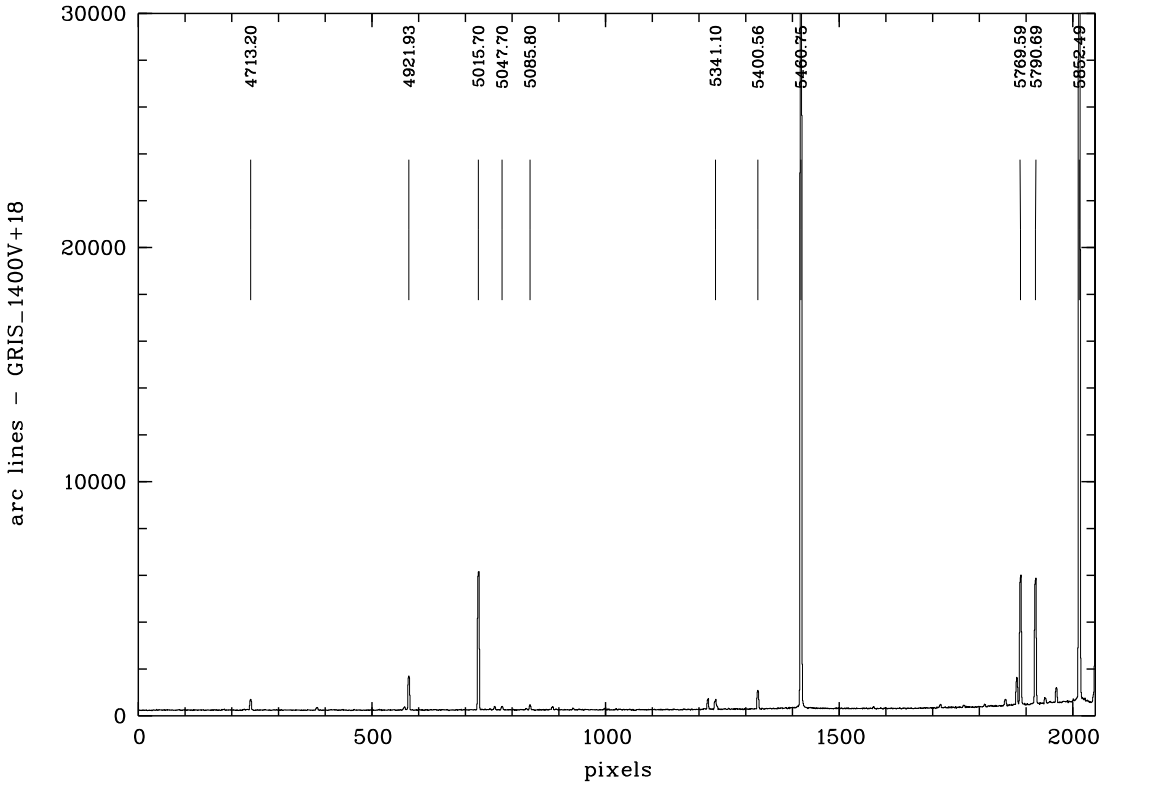


Figure D.2: Calibration spectrum taken with the SR collimator and grism GRIS_1400V+18

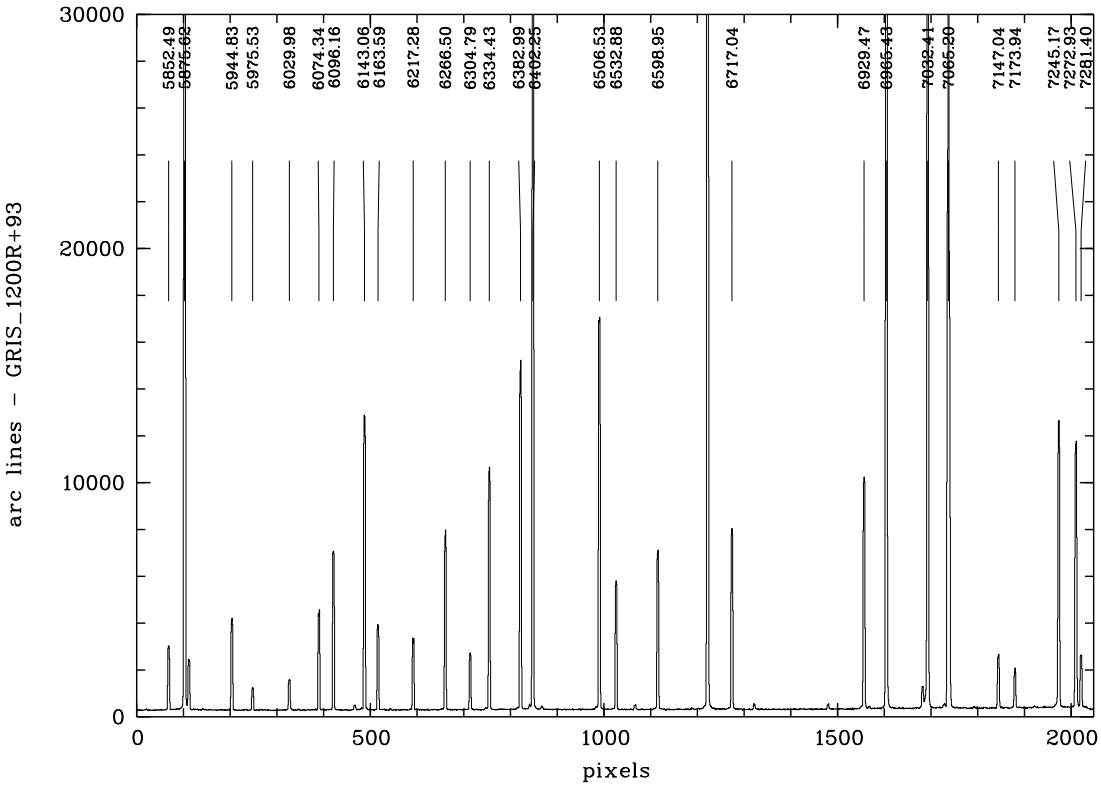


Figure D.3: Calibration spectrum taken with the SR collimator and grism GRIS_1200R+93

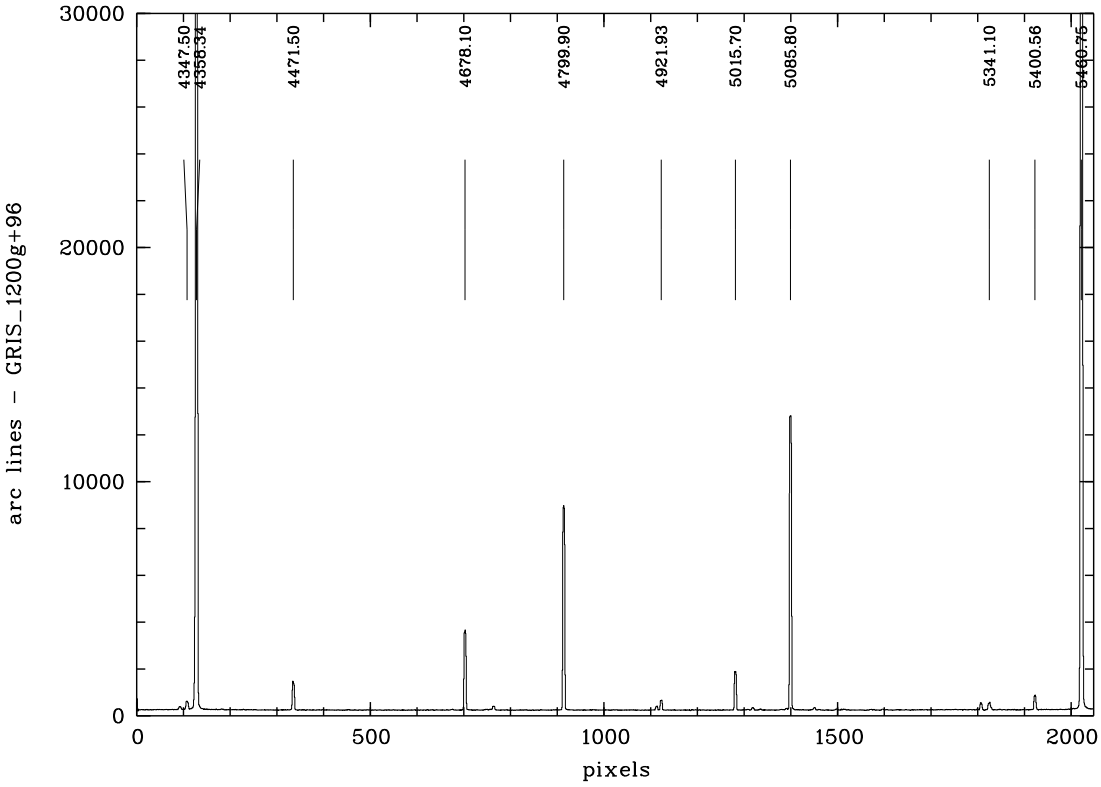


Figure D.4: Calibration spectrum taken with the SR collimator and grism GRIS_1200g+96

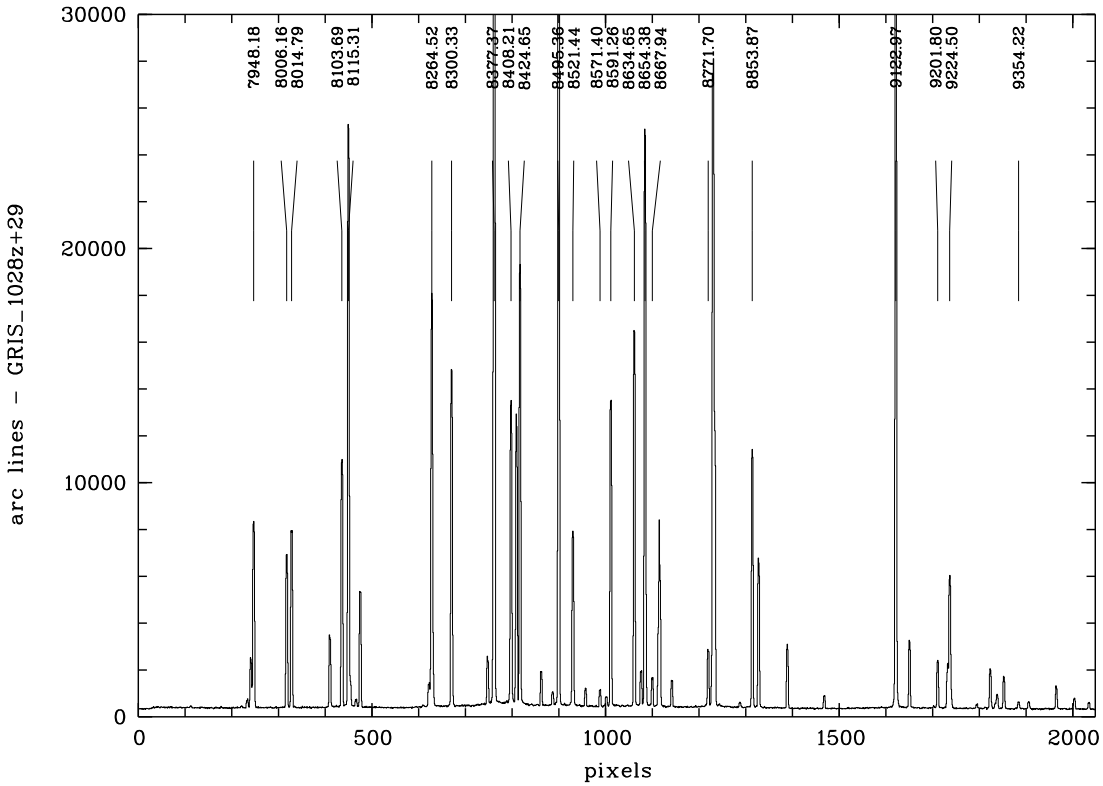


Figure D.5: Calibration spectrum taken with the SR collimator and grism GRIS_1028z+29

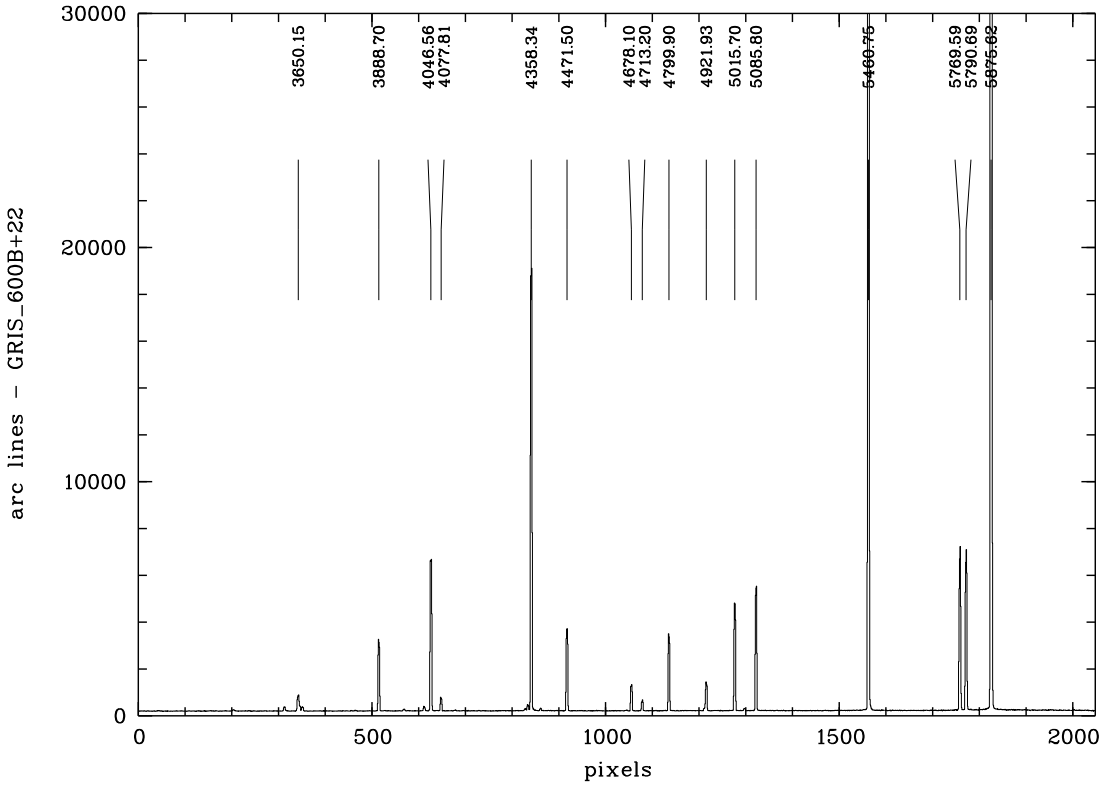


Figure D.6: Calibration spectrum taken with the SR collimator and grism GRIS_600B+22

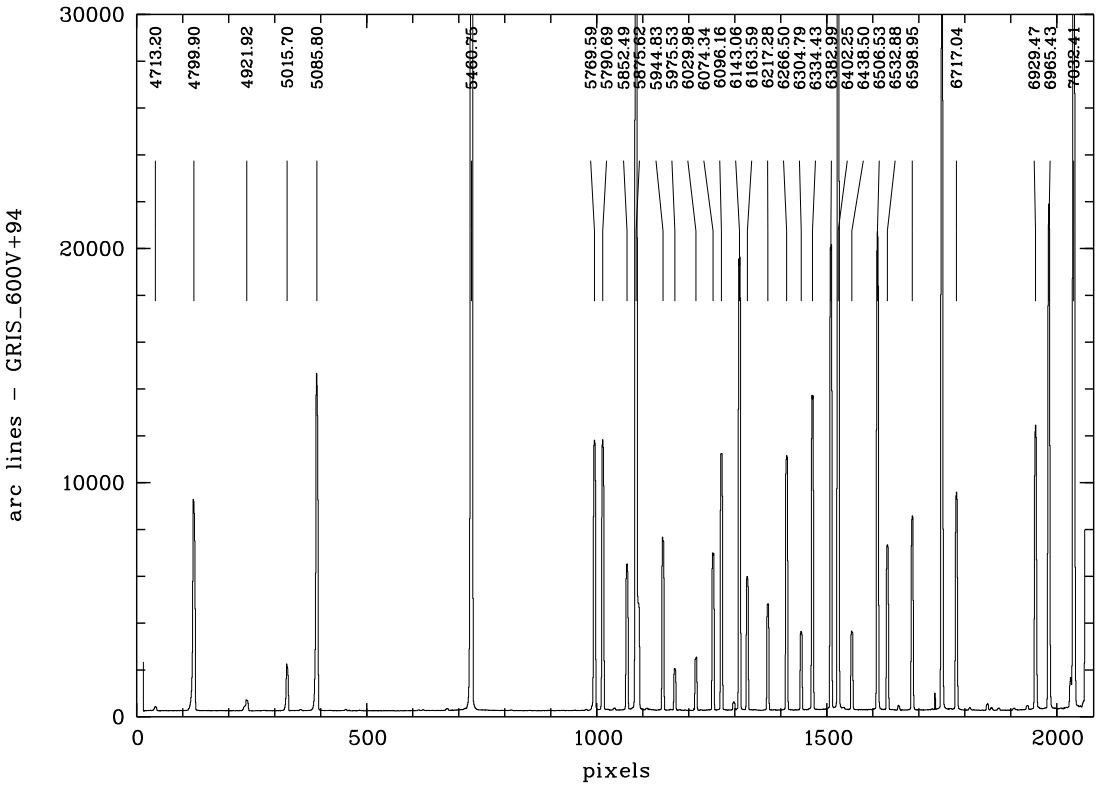


Figure D.7: Calibration spectrum taken with the SR collimator and grism GRIS_600V+94

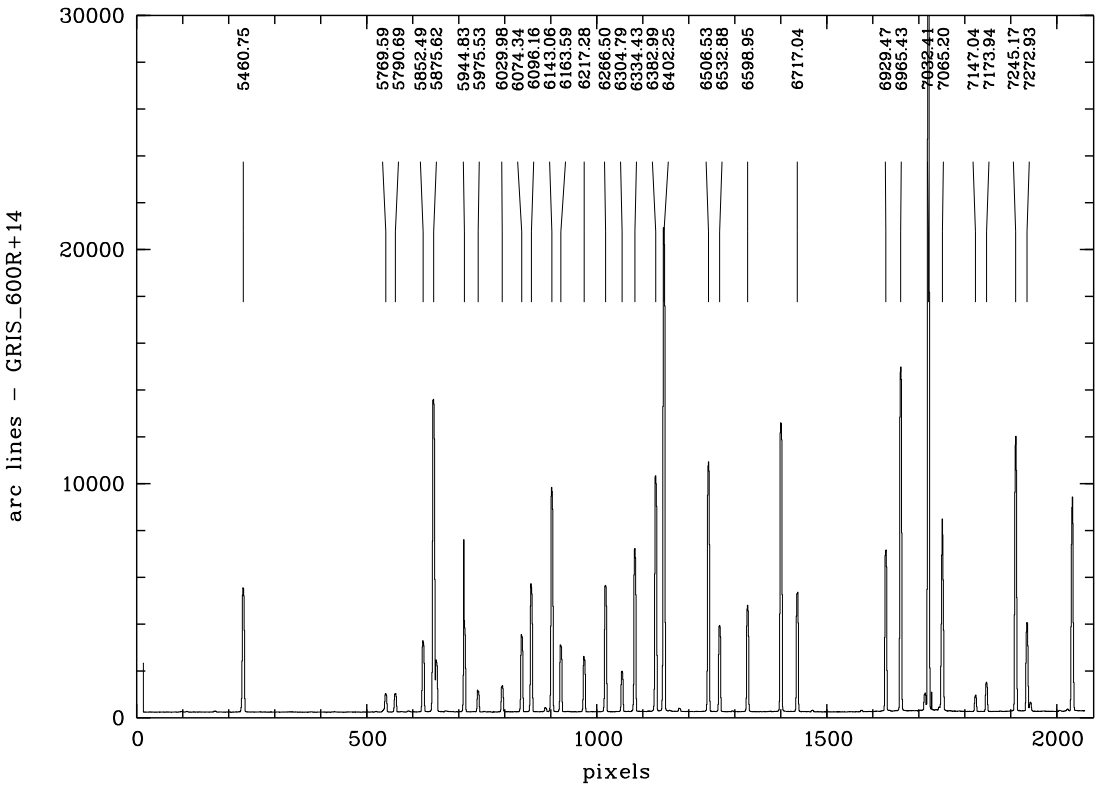


Figure D.8: Calibration spectrum taken with the SR collimator and grism GRIS_600R+14

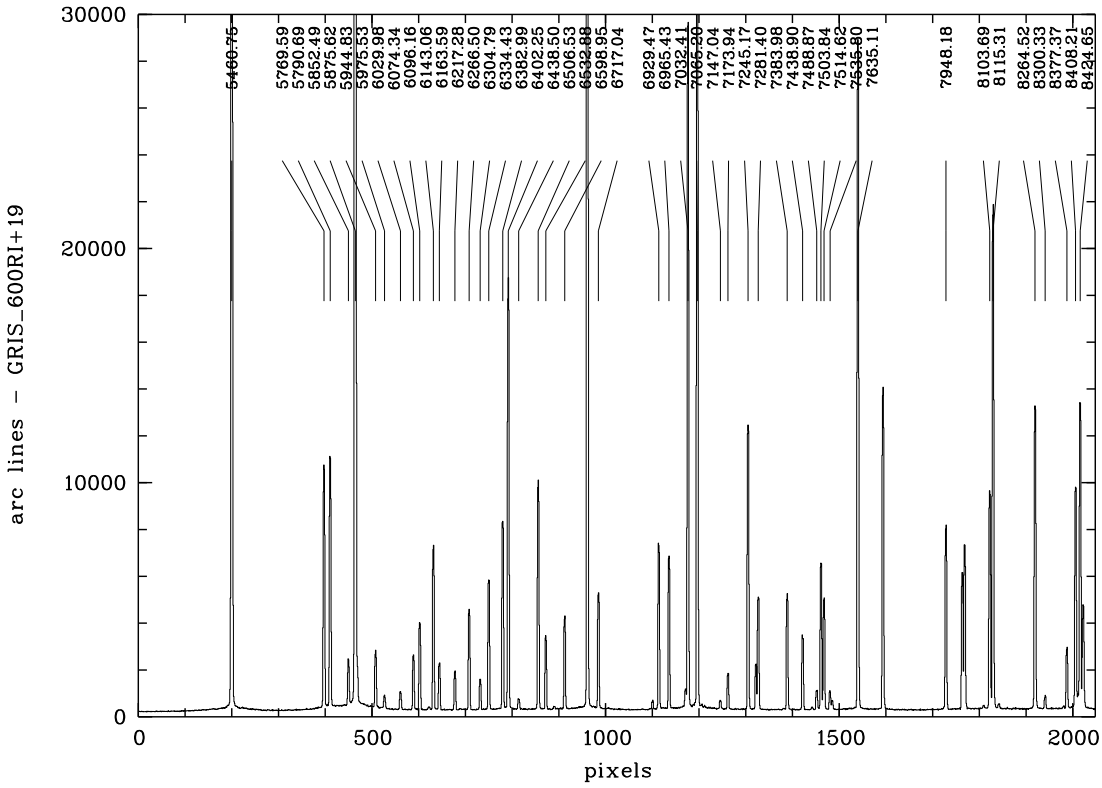


Figure D.9: Calibration spectrum taken with the SR collimator and grism GRIS_600RI+19

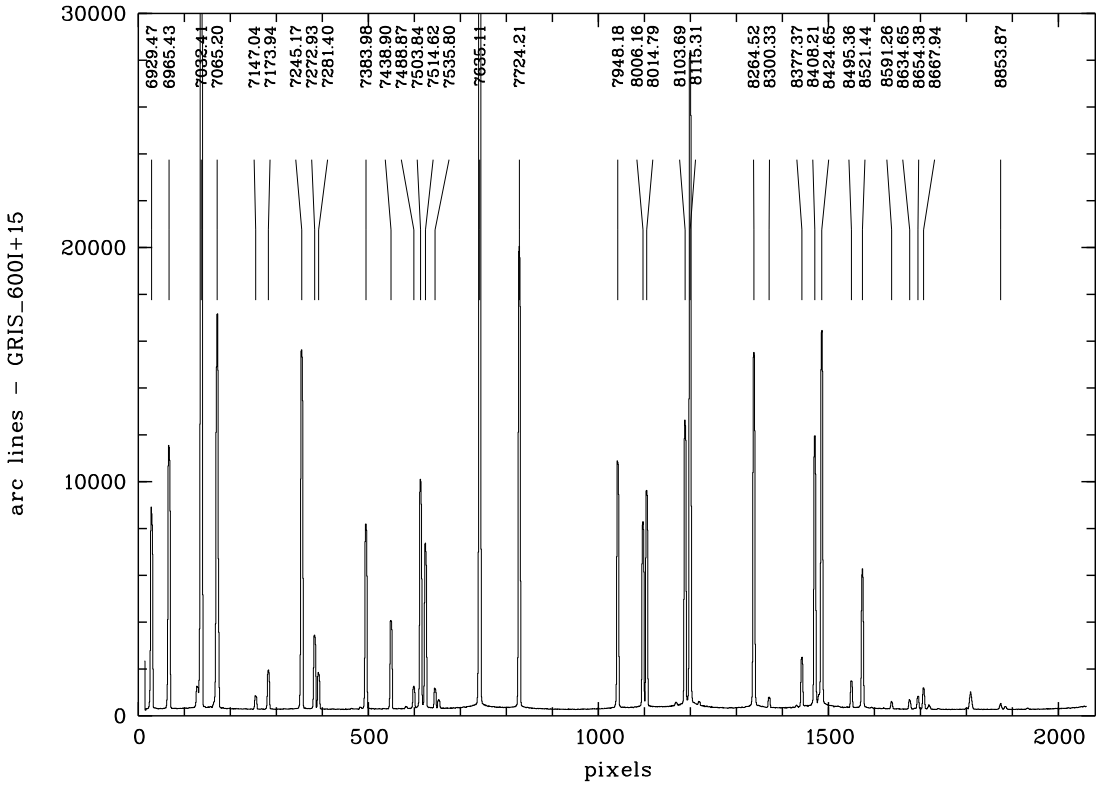


Figure D.10: Calibration spectrum taken with the SR collimator and grism GRIS_600I+15

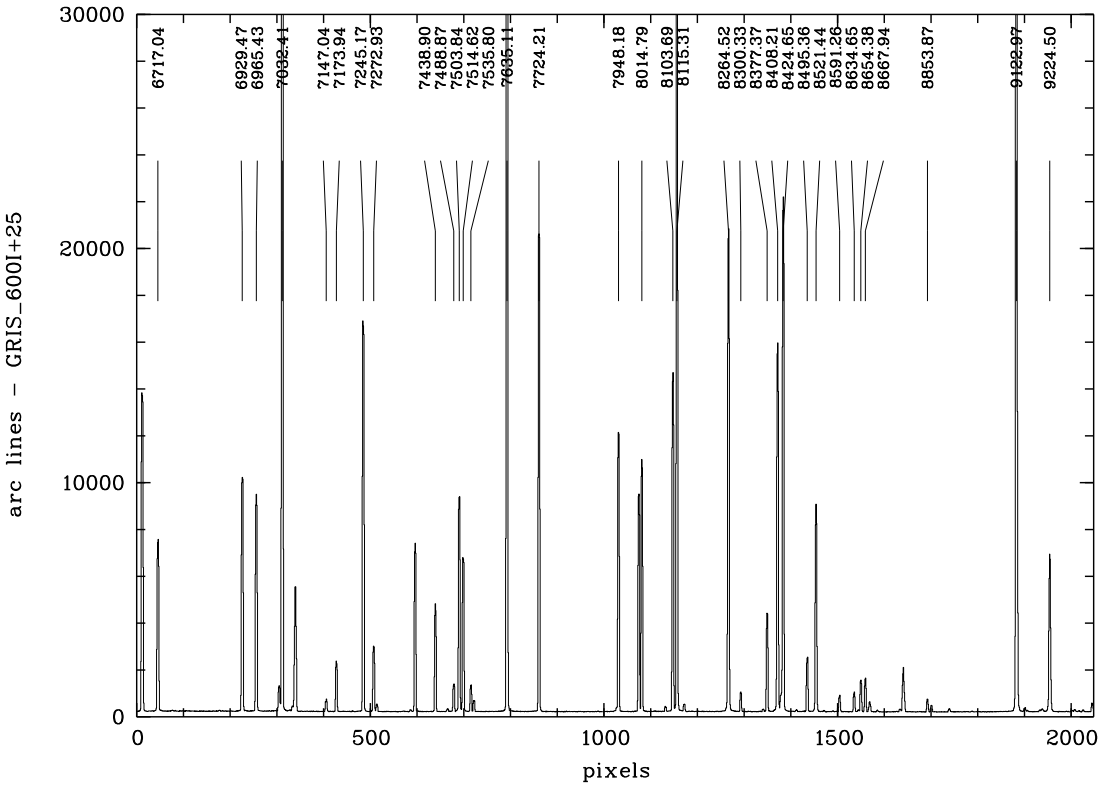


Figure D.11: Calibration spectrum taken with the SR collimator and grism GRIS_600I+25

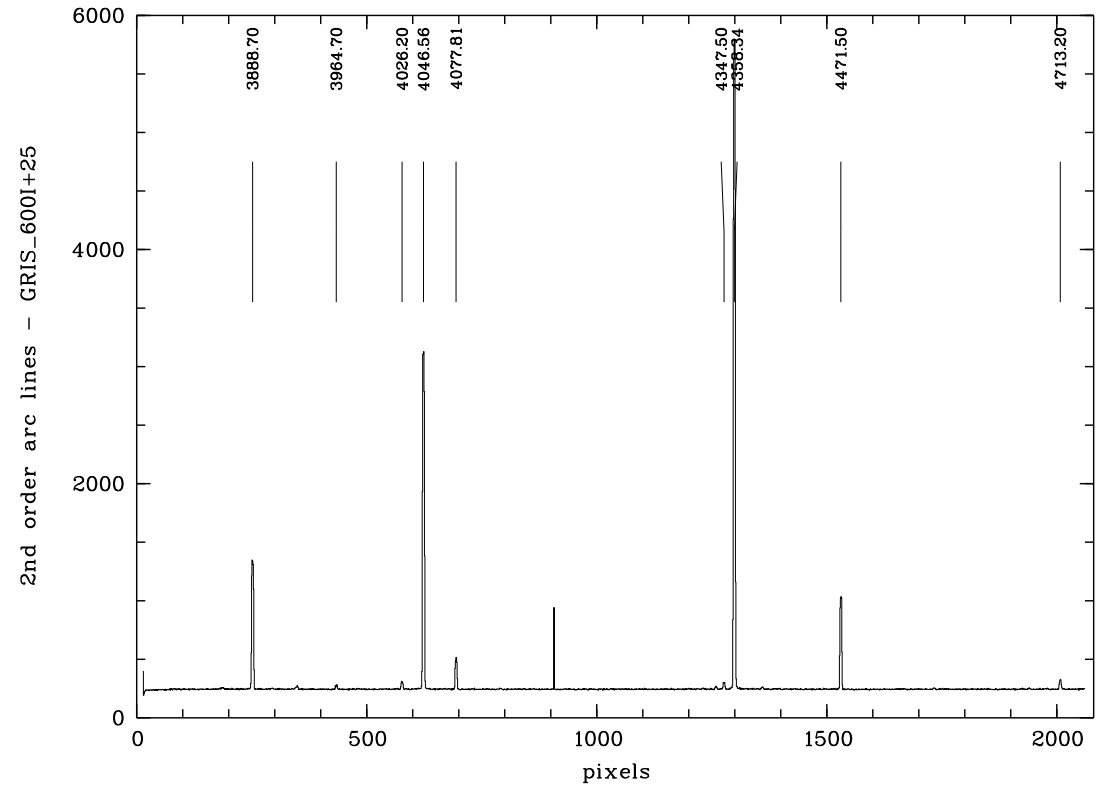


Figure D.12: 2nd order calibration spectrum taken with the SR collimator and grism GRIS_600I+25

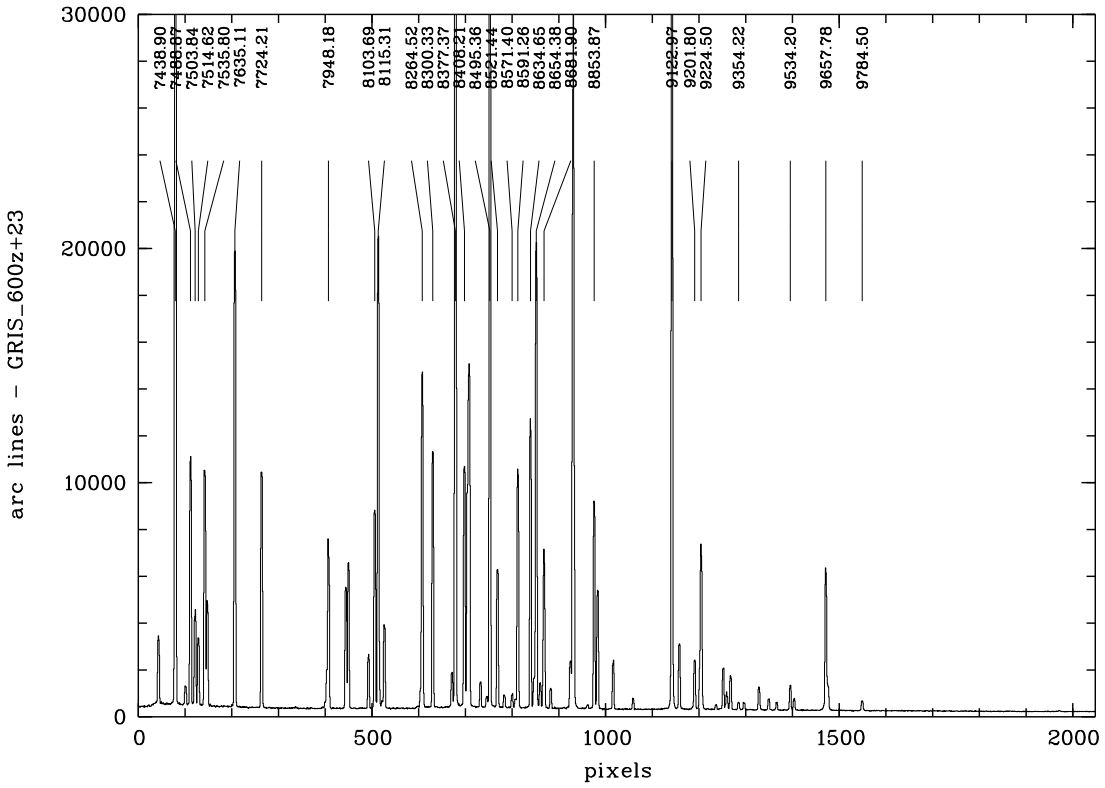


Figure D.13: Calibration spectrum taken with the SR collimator and grism GRIS_600z+23

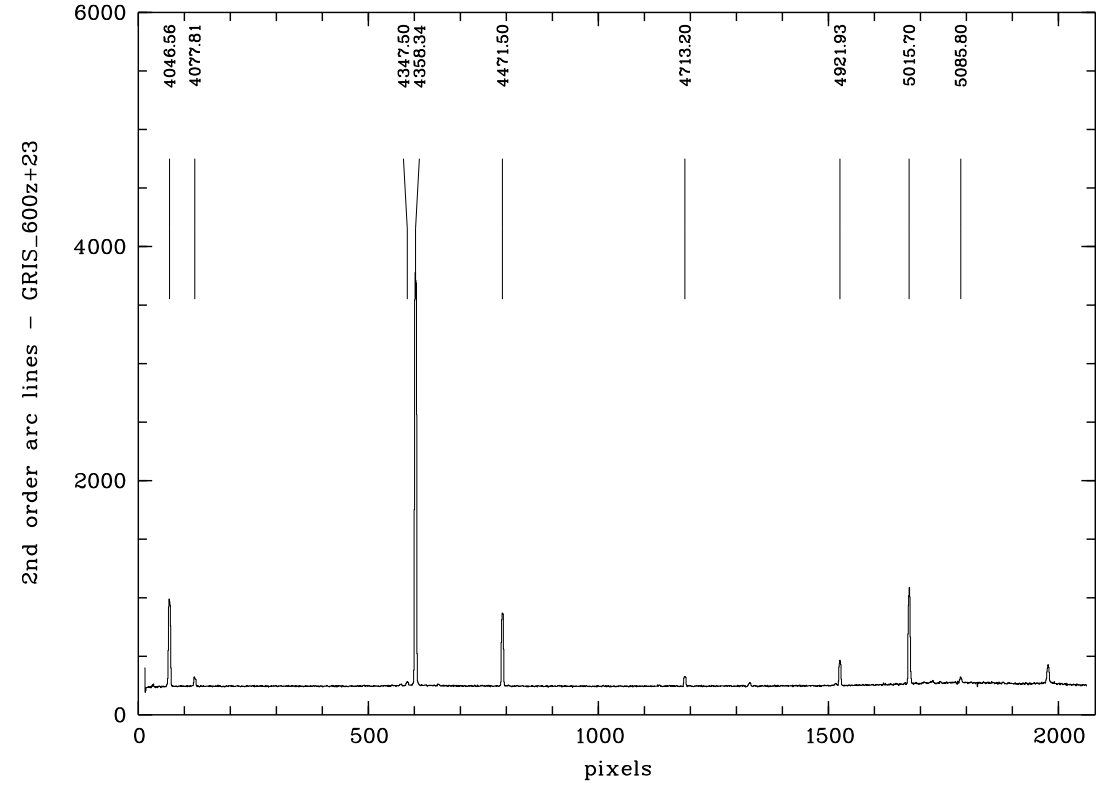


Figure D.14: 2nd order calibration spectrum taken with the SR collimator and grism GRIS_600z+23

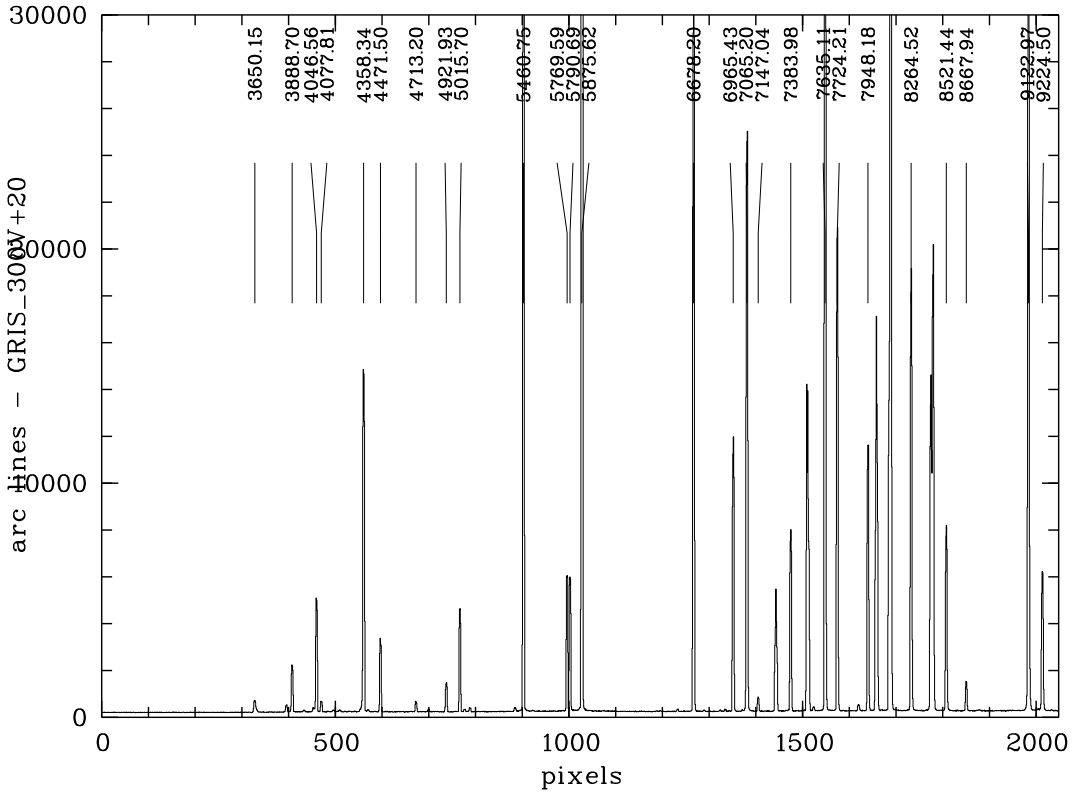


Figure D.15: Calibration spectrum taken with the SR collimator and grism GRIS_300V+20 (useful also for GRIS_300V+10)

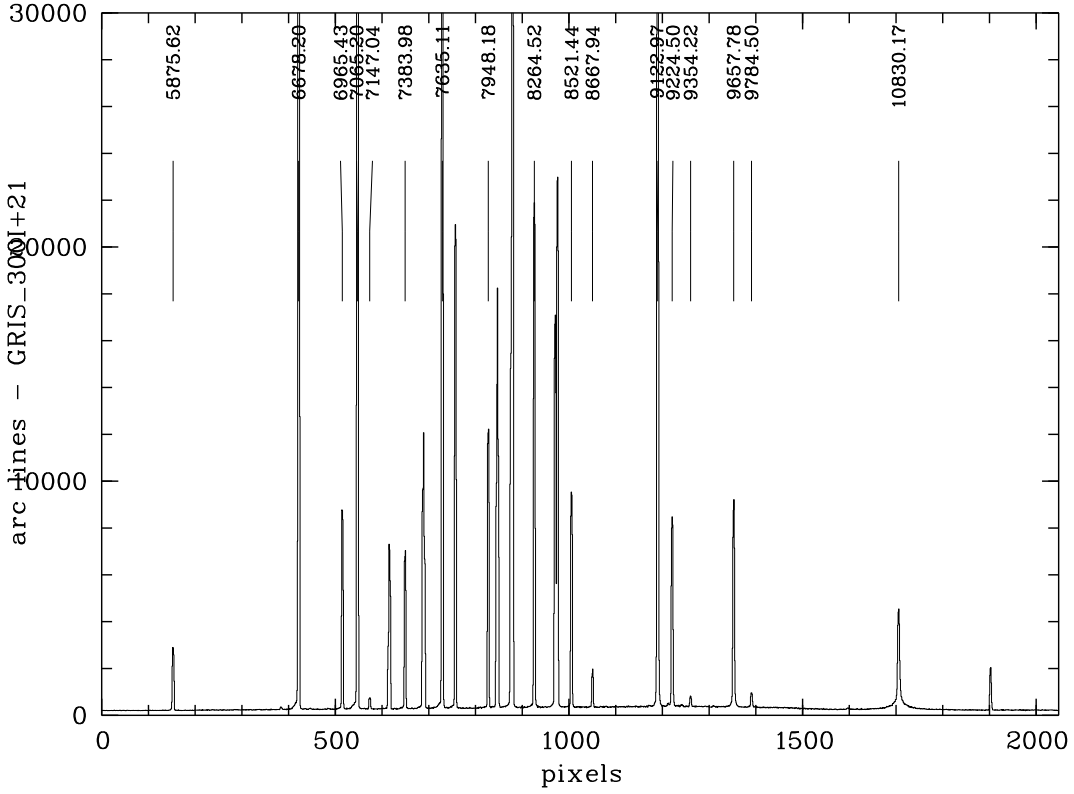


Figure D.16: Calibration spectrum taken with the SR collimator and grism GRIS_300I+21

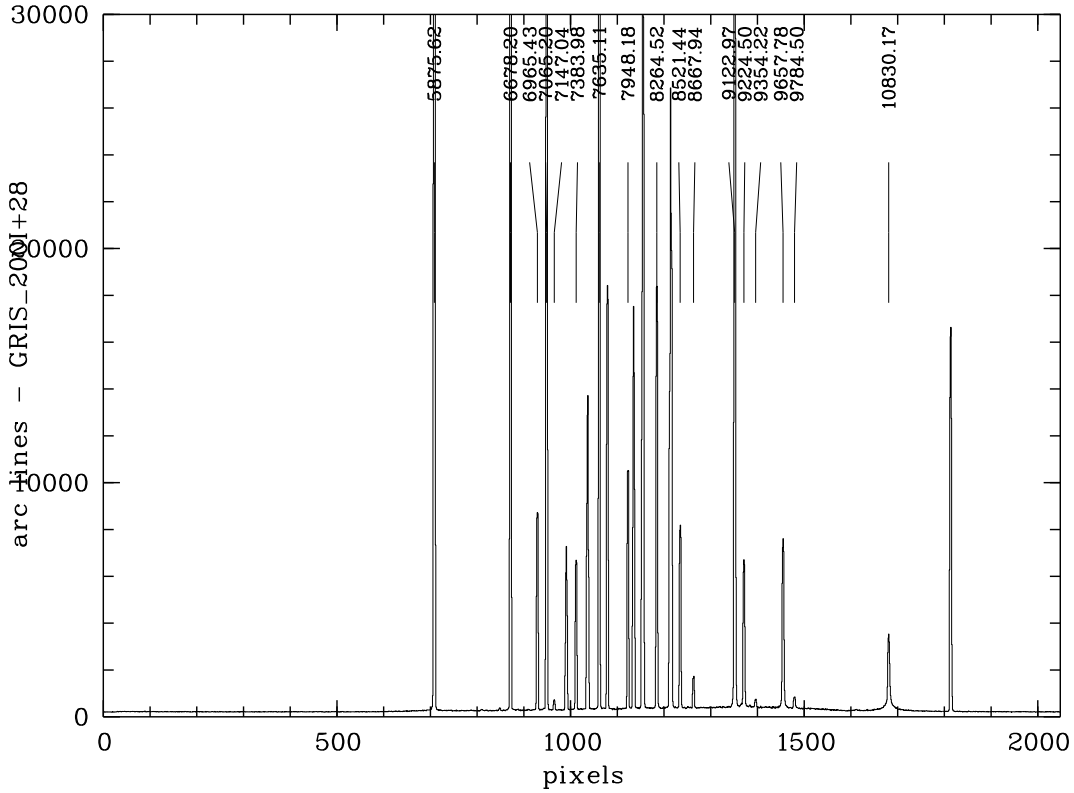


Figure D.17: Calibration spectrum taken with the SR collimator and grism GRIS_200I+28

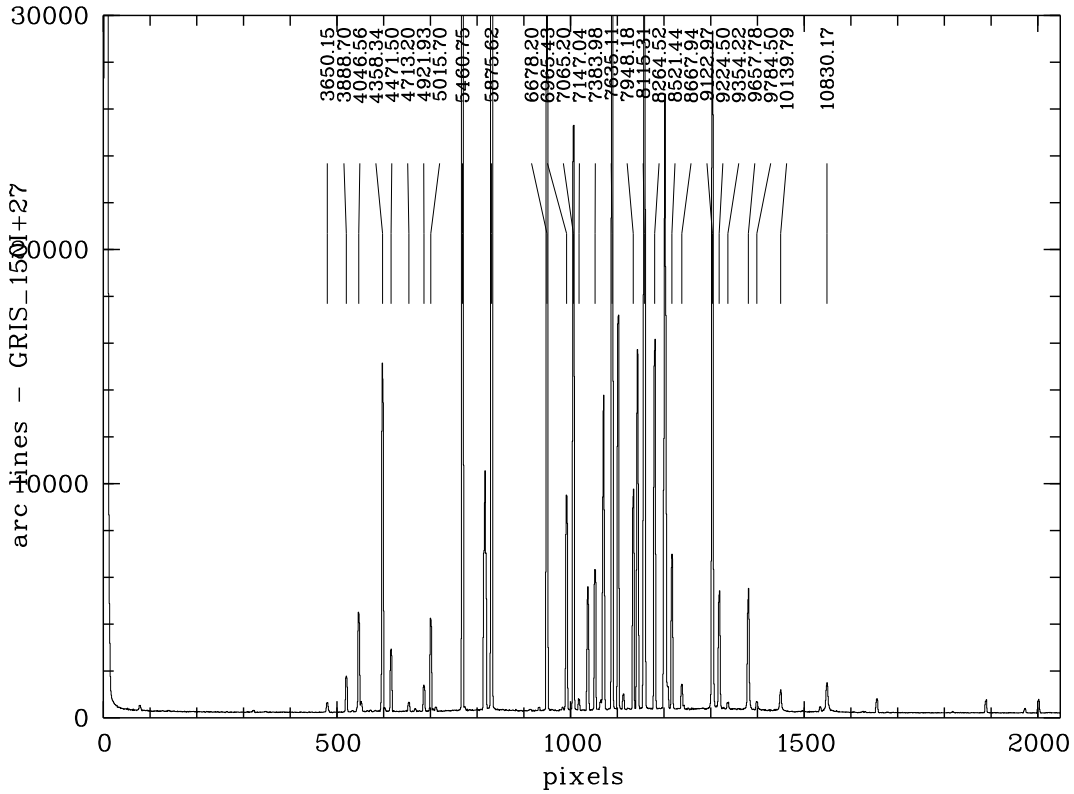


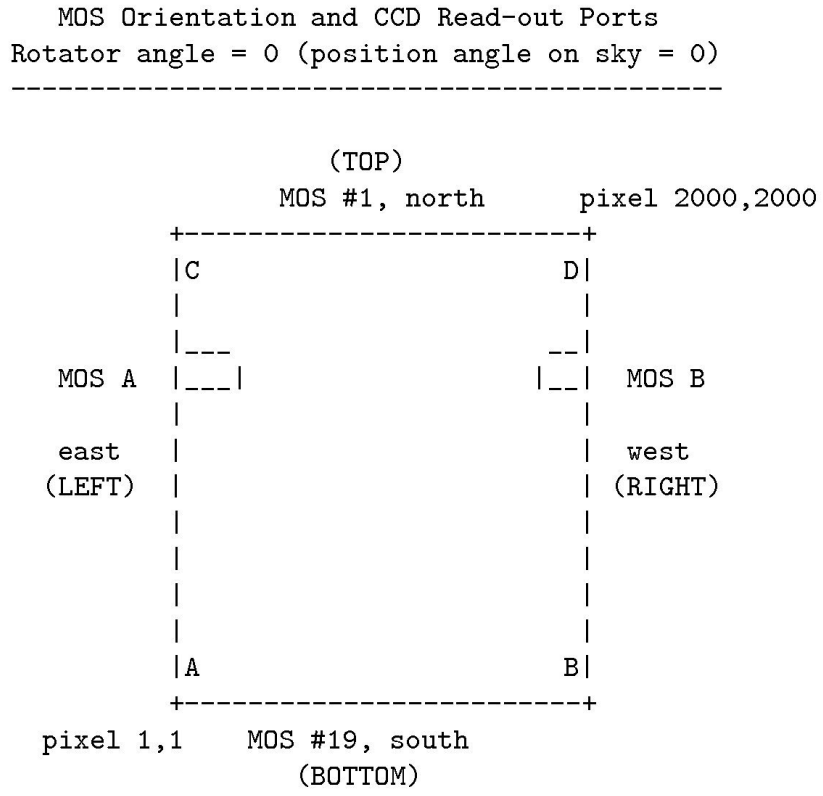
Figure D.18: Calibration spectrum taken with the SR collimator and grism GRIS_150I+27

Appendix E

FORS Image Orientation

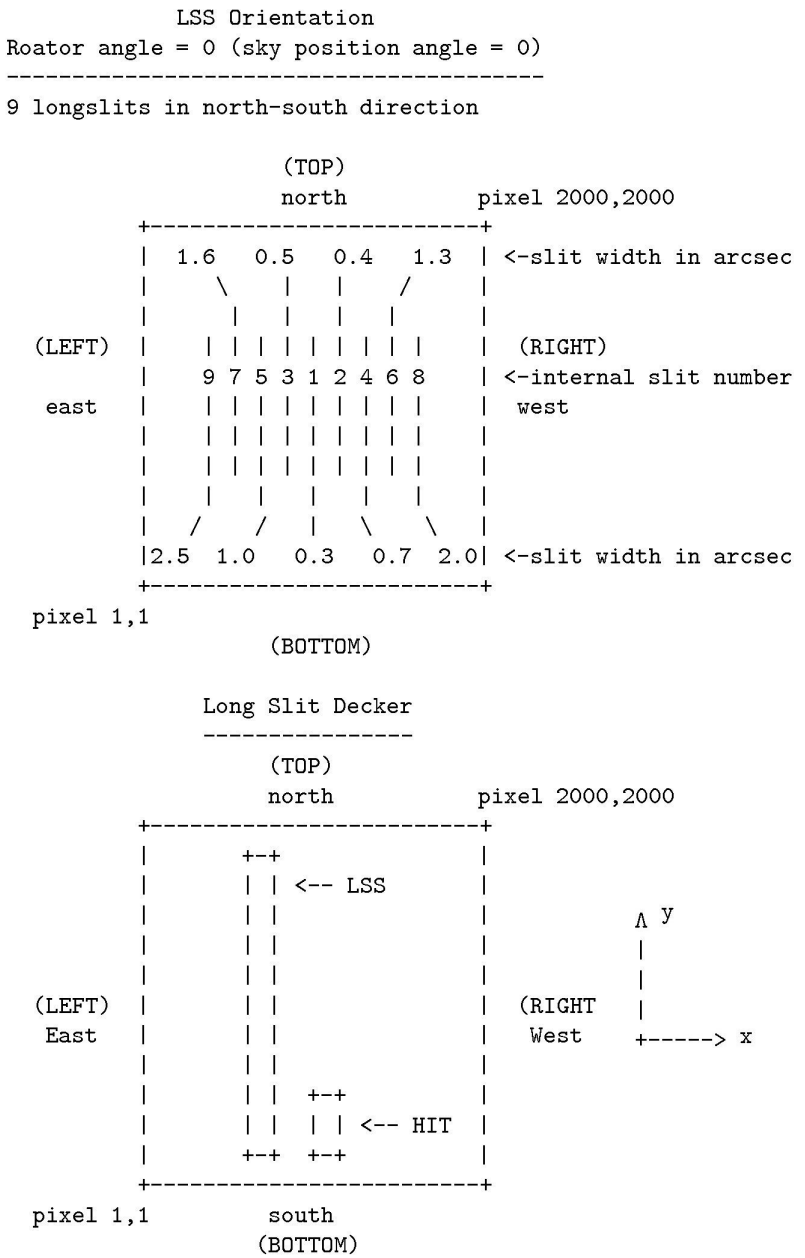
E.1 MOS Orientation

The orientation of the FORS image in MOS mode is given below for rotator position 0 deg. Note that the sky directions in this schematics change for different rotator angles while the orientation on the CCD remains unchanged. The orientation of the images on the CCD is given in parenthesis. The locations of the CCD readout ports are also shown.



E.2 LSS Orientation

The orientation of the FORS image in LSS mode is given below for rotator position 0 deg. Note that the sky directions in this schematics change for different rotator angles while the orientation on the CCD remains unchanged. The orientation of the images on the CCD is given in parenthesis.



The x-distance between HIT decker and LSS decker is half the distance between two LSS slits. If HIT decker enables 0.3'' slit, the LSS decker will enable the large pinhole close to the center of the field of view.

Appendix F

World Coordinate System Information

The header of the FITS file used for preparing a FORS target mask with FIMS should contain the following keywords, for a linear scale:

```
CTYPE1 =          'RA---TAN'     / tangential projection type
CRVAL1 =          12.345678      / x- coord of reference pixel:  RA in deg
CRPIX1 =          512.0          / x coord of reference pixel:  PIXEL
CTYPE2 =          'DEC--TAN'     / tangential projection type
CRVAL2 =          -12.34567      / y- coord of reference pixel:  DEC in deg
CRPIX2 =          525.5          / y coord of reference pixel:  Pixel

CDELT1 =          -3.234E-5      / x- scale:  degrees per pixel
CROTA1 =          10.0           / rot in degrees, from N to E
CDELT2 =          3.234E-5       / y- scale:  degrees per pixel
CROTA2 =          10.0           / rot in degrees, from N to E

EQUINOX =         2000.0         / equinox
```

Beside this conventional `CROTA/CDELT`-notation there is also the `PCiiijjj/CDELT`-notation in use, in particular for ESO instruments, where PC keywords are the rotation matrix:

```
CTYPE1 =          'RA---TAN'     / tangential projection type
CRVAL1 =          12.345678      / x- coord of reference pixel:  RA in deg
CRPIX1 =          512.0          / x coord of reference pixel:  PIXEL
CTYPE2 =          'DEC--TAN'     / tangential projection type
CRVAL2 =          -12.34567      / y- coord of reference pixel:  DEC in deg
CRPIX2 =          525.5          / y coord of reference pixel:  Pixel

CDELT1 =          -3.234E-5      / x- scale:  degrees per pixel
CDELT2 =          3.234E-5       / y- scale:  degrees per pixel
PC001001 =        0.9848         / cos(CROTA)
PC001002 =        0.1736         / - sin(CROTA)
PC002001 =        0.9848         / sin(CROTA)
PC002002 =        0.1736         / cos(CROTA)

EQUINOX =         2000.0         / equinox
```

A third notation for WCS FITS header keywords is the `CDi_j` notation. Transformation formulae between the different keyword notations are given in "A Users Guide for the Flexible Image Transport System (FITS)" (version 3.1, NASA), "Definition of the Flexible Image Transport System (FITS)" (NOST 100-1.2) and the "Data Interface Control Document" (GEN-SPE-ESO-19400-0794).

```
CTYPE1 =          'RA---TAN'     / tangential projection type
CRVAL1 =          12.345678      / x- coord of reference pixel:  RA in deg
CRPIX1 =          512.0          / x coord of reference pixel:  PIXEL
CTYPE2 =          'DEC--TAN'     / tangential projection type
CRVAL2 =          -12.34567      / y- coord of reference pixel:  DEC in deg
CRPIX2 =          525.5          / y coord of reference pixel:  Pixel

CD1_1 =           3.185E-5       / partial derivative
CD1_2 =           -5.616E-5      / partial derivative
CD2_1 =           5.616E-5       / partial derivative
CD2_2 =           3.185E-5       / partial derivative

EQUINOX =         2000.0         / equinox
```

Appendix G

Field vignetting with the MIT CCD

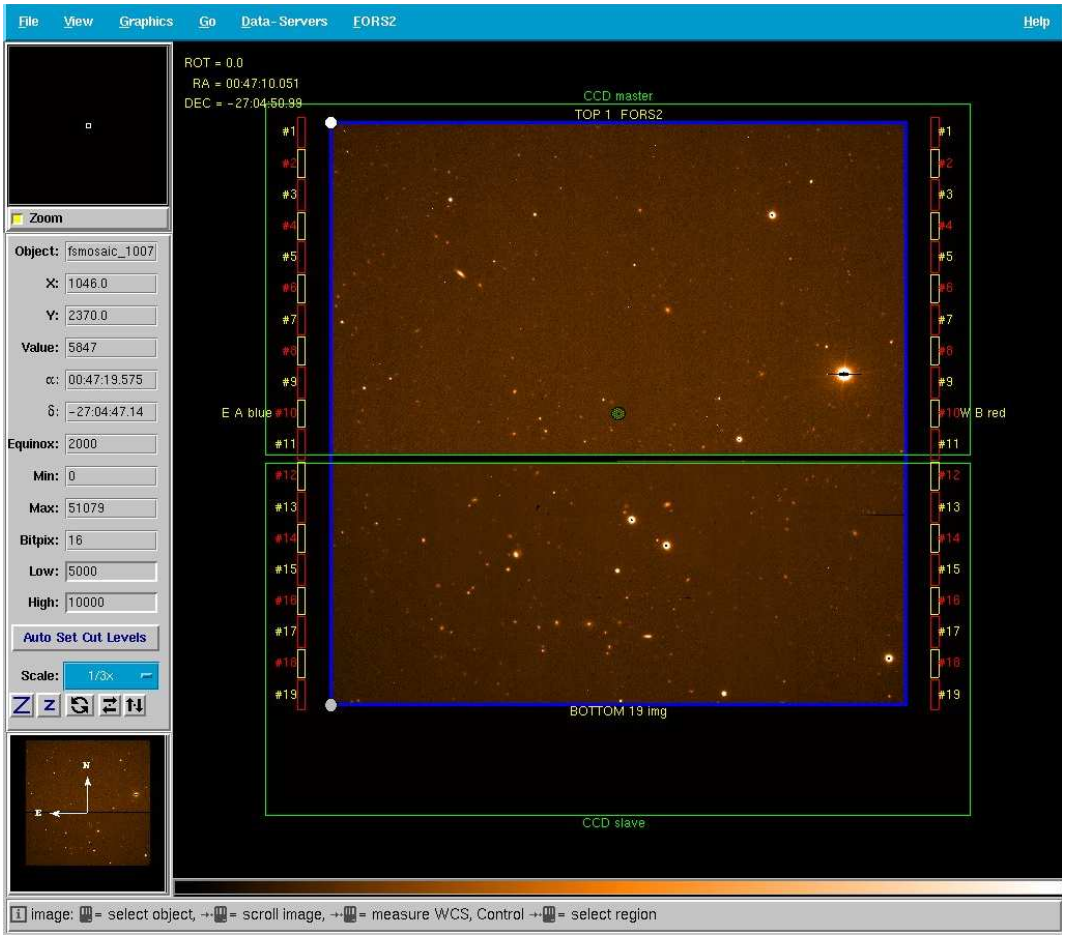


Figure G.1: The field of view of FORS2 with MIT CCDs is restricted by the MOS unit in the focal plane of the unit telescope to about 6.8 arc-minutes for the standard resolution collimator.

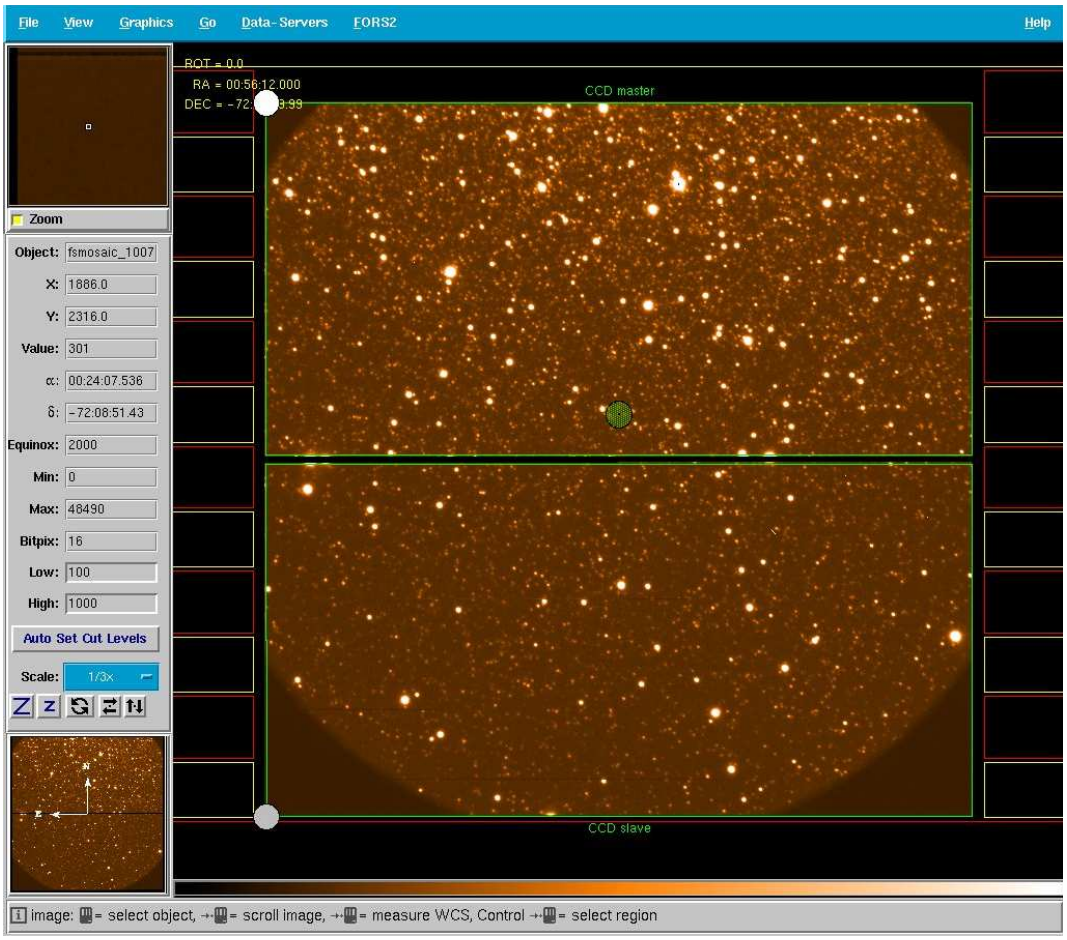


Figure G.2: In case of the high resolution collimator the corners of the field of view are vignetted by the camera lenses.

Appendix H

'Retired' Instrument Components/Modes

Removed Component	Used in	Availability	Reason for Removal	Replacement
H_Alpha+59	FORS1+2	1/4/99-30/9/00	ghosts	H_Alpha+83
GRIS_600z+16	FORS1	1/4/00-31/3/01	low response	GRIS_600z+26
GRIS_600R+24	FORS2	1/4/00-31/3/02	low response	GRIS_600RI+19
XGRIS_600V+90	FORS2		no red Echelle	none
XGRIS_300I+91	FORS2		no red Echelle	none
2k×2k Site CCD	FORS2	1/4/00-31/3/02	red optimization	MIT mosaic
GRIS_600z+26	FORS1+2	1/4/00-31/9/02	low response	none
GRIS_600I+15	FORS1	1/4/00-31/3/07	low response	none
GRIS_300I+15	FORS1	1/4/00-31/3/07	low response	none

Table H.1: "Retired" instrument components

		old Tektronix FORS1 CCD		old SITE FORS2 CCD	
port	gain	RON [e^-]	K [e^-/ADU]	RON [e^-]	K [e^-/ADU]
A	high	5.13±0.11	1.37±0.02	5.2±0.1	1.85±0.03
B	high	5.57±0.11	1.70±0.04	5.5±0.1	2.00±0.02
C	high	5.76±0.10	1.62±0.02	5.3±0.1	1.90±0.02
D	high	5.87±0.15	1.73±0.03	5.5±0.1	1.83±0.05
A	low	5.89±0.16	2.74±0.06	5.6±0.1	2.62±0.03
B	low	6.23±0.17	3.35±0.06	5.9±0.1	2.81±0.05
C	low	6.27±0.10	3.17±0.05	5.8±0.1	2.68±0.04
D	low	6.40±0.15	3.31±0.06	5.7±0.1	2.61±0.03

Table H.2: The old FORS1 and FORS2 CCDs
Detector readout noise and conversion factors of the old Tektronix and SITE FORS1 and FORS2 CCDs. Port A of FORS1 is the lower left, B the lower right, C the upper left and D the upper right quadrant.

- Table H.1 lists the instrument components which are no longer offered for FORS and the time period during which they were used.
- The Echelle mode with the two conventional grisms was known to perform bad in terms of its instrument response. It was officially decommissioned in P77. To replace it a new volume phased holographic grism has been installed with a response 3x higher than the Echelle mode (or the respective 2nd order observations which also show relatively low performance). The wavelength range is 3730 to 4970 Å with the central wavelength at 4340Å and a dispersion of 0.61 Å/pxl. The spectral resolution is equal to 1420 for a slit width of 1".
- The Second-order observations were not supported beyond P82, as there was little or no demand for them and the space was needed in the instrument for more frequently used Grisms and filters.

- The MOS was not offered with the HR-collimator following the upgrade of FORS1 to the E2V mosaic. Users should use the un-binned mode instead for applications requiring such observations.
- Table H.2 lists the readout noise and conversion factors of the old FORS1 and FORS2 CCDs.

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